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Calculation and Design of
Alternating Current Lift Magnets

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CALCULATION AND DESIGN OF
ALTERNATING CURRENT LIFT MAGNETS

BY

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B. S. Ohio University, 1907

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THESIS

Submitted in Partial Fulfillment of the Requirements for the

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May 31 1911

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

FRANCIS MARION PORTER

ENTITLED "THE CALCULATION AND DESIGN OF ALTERNATING
CURRENT LIFTING MAGNETS".

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE IN PHYSICS

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Recommendation concurred in:

} Committee
on
Final Examination



CONTENTS.

- * -

Introduction	page. 1.
Theoretical Consideration	3.
Preliminary Investigation	14.
Description of Apparatus	20.
Description of Method	24.
Discussion of Results	27.
Summary	30.
Data	31.
Curves	43.
Bibliography	58.

INTRODUCTION.

- * -

There appeared recently in a leading technical journal an article* in which the author, through a mathematical consideration, arrives at the conclusion that for equal maximum induction the lifting powers of single-phase, continuous, and three-phase current magnets are in the proportion 1 : 2 : 3 respectively. Owing to the constantly increasing use of alternating current systems for power as well as for lighting, this conclusion, if true, is of remarkable commercial importance. Already a successful duplication of continuous current apparatus for other purposes than lifting magnets has been achieved for alternating current use. Naturally this condition creates a demand for an alternating current lifting magnet that will operate with satisfactory efficiency, especially as compared with that of the continuous current magnet.

The laws governing the pull, range, heating, efficiency, etc., of continuous current electromagnets are now generally known, so that their design is comparatively an easy matter. But in considering the case of the alternating current magnet not only must the various general principles of the continuous current magnet be followed, but there are many additional factors which change entirely the characteristics. It is hoped in this paper to find a method

*"Calculation of Alternating Current Lifting Magnets". J. Liska.
Elek. Zeit., 29 Sept. 1910, p. 985.

by which, having given the various conditions under which a lift magnet is to be operated, it may be successfully designed for alternating current use. In view of the fact that the problem is one with many and uncertain variables, the aim is to reach some definite conclusions that may be expressed in a general way, sufficiently accurate and convenient for the designer, rather than with great mathematical precision. If possible the above mentioned conclusions regarding the relative pull of continuous current and single-phase and three-phase currents will be verified by experimental means.

THEORETICAL CONSIDERATION.

- * -

Symbols used throughout this discussion.

- - - - -

- P = weight lifted, expressed in kg.
- A = cross-sectional area of pole-face, in cm^2 .
- n = number of turns in coil.
- D = thickness of winding, in cm.
- l = length of coil, in cm.
- C = mean circumference of one turn of winding, in cm.
- S = area of cross-section of space between core and coil, in cm.
- s = length of air-gap, in cm.
- B = induction in one phase, in iron.
- B' = induction, constant, between core and coil.
- f = frequency, in cycles per second.
- E' = applied potential, per phase.
- E_c = induced e.m.f., per phase.
- r = resistance of winding, per phase.
- x_g = reactance of air-gap, in ohms.
- x = total leakage reactance, per phase.
- I = current in coil, per phase.
- Z = total impedance, per phase.

1. Determination of the Expression for the Lifting Power.

- * -

When a current of electricity flows in a conductor the energy of the induced magnetic field, expressed in the c.g.s. system, is*

$$W = \frac{1}{8\pi} \int_{\tau} \frac{B^2}{\mu} d\tau \quad (1)$$

in which B represents the induction, and μ the permeability of the substance constituting the path of the flux, and τ the entire space through which the field extends.

If we consider the case represented by Figure 1 wherein there is an iron core of known permeability and an air-gap, it is evident that (1) may be written

$$\begin{aligned} W &= W_{\text{air}} + W_{\text{iron}} \\ &= \frac{1}{8\pi} \int_s B^2 d\tau + \frac{1}{8\pi} \int_i \frac{B^2}{\mu} d\tau \quad (2) \end{aligned}$$

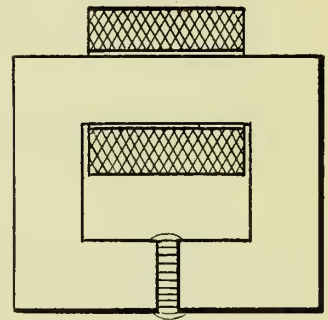


FIG. 1.

where $\underline{s}$ is the length of the air-gap and $\underline{i}$ is the length of the magnetic circuit in iron. If we put

$$d\tau = dA \cdot dl$$

where A is the area of cross-section and l is the length of the magnetic circuit, then

$$W = \frac{1}{8\pi} \iint_{A_0}^s B^2 dA \cdot dl + \frac{1}{8\pi\mu} \iint_{A_0}^l B^2 dF \cdot dl \quad (3)$$

We here regard μ as constant, since for iron it is very large in comparison with what it is for air, and therefore W_{iron} becomes

* See Maxwell's "Treatise on Electricity and Magnetism" Vol.II, Art. 633.

very small as compared with W_{air} .

If the length of the air-gap is varied the energy also changes; and the mechanical force with which the poles tend to approach each other is equal to the variation of the energy with respect to the length of the gap, s^* .

$$P = \frac{\partial W}{\partial s} = \frac{\partial}{\partial s} \left(\frac{1}{8\pi} \int_A \int_0^s B^2 dA \cdot dl + \frac{1}{8\pi \mu} \int_A \int_0^l B^2 dA \cdot dl \right)$$

$$= \frac{1}{8\pi} B^2 dA = \frac{1}{8\pi} B^2 A \quad \text{dynes} \quad (4)$$

if B is constant. Or

$$P = \frac{1}{8\pi} \cdot \frac{1}{981} \cdot B^2 \cdot A \cdot 10^{-3} \quad \text{kg.}$$

$$= 4.07 B^2 \cdot A \cdot 10^{-8} \quad \text{kg.} \quad (5)$$

This expression, which is true only when B is constant, is therefore the lifting power of direct current magnets.

If the coils of the magnet be energized by a single-phase current, B varies according to the sine law. The lifting power for the time t is therefore

$$P_t = \frac{1}{8\pi} 2 \cdot B^2 \cdot \sin^2 \omega t A \quad (6)$$

if B represents the effective value. Or,

$$P_t = \frac{1}{8\pi} \cdot B^2 \cdot A \cdot (1 - \cos \omega t) \quad (7)$$

that is, the lifting power varies with twice the frequency about the mean value

* For the exact proof of this see F. Emde, "On the Calculation of Electro-magnets", Elektrotechnik u. Maschinenbau, 1906, S. 945.

$$P = \frac{1}{8\pi} B^2 \cdot A \quad \text{dynes}$$

Or $P = 4.07 B^2 \cdot A \cdot 10^{-8} \quad \text{kg.} \quad (8)$

With a three-phase exciting current the three inductions have for their three instantaneous values

$$\sqrt{2} B \sin(\omega t)$$

$$\sqrt{2} B \sin(\omega t - 120^\circ)$$

and $\sqrt{2} B \sin(\omega t - 240^\circ)$

where, as before, B represents the effective value. The lifting power, on substituting these values in (4), becomes,

$$P = \frac{1}{8\pi} 2B^2 A [\sin^2 \omega t + \sin^2(\omega t - 120^\circ) + \sin^2(\omega t - 240^\circ)] \quad (9)$$

This reduces to

$$\begin{aligned} P &= \frac{1}{8\pi} 3 B^2 A \quad \text{dynes} \\ &= \frac{3}{8\pi \cdot 981} B^2 \cdot A \cdot 10^{-3} \quad \text{kg.} \\ &= 12.21 B^2 A 10^{-8} \quad \text{kg.} \quad (10) \end{aligned}$$

That is, for a given value of B the lifting power is constant for a three phase magnet.

If in these three expressions we substitute the maximum value of the induction, which is the one most frequently considered, the lifting powers for the single-phase, continuous current and three-phase current become respectively

$$P_1 = 2.035 B_{\max}^2 A 10^{-8} \quad \text{kg.} \quad (11)$$

$$P_2 = 4.07 B_{\max}^2 A 10^{-8} \quad \text{kg.} \quad (12)$$

$$P_3 = 6.1 B_{\max}^2 A 10^{-8} \quad \text{kg.} \quad (13)$$

Thus we see that for equal maximum induction the lifting powers bear the relation of 1 : 2 : 3 .

For the case of a two phase magnet* in which the impressed e.m.f.'s are 90° apart, assume the instantaneous values of the induction in the two coils to be B' and B'' . Each will be cyclic, and we will have

$$B' = K \sin \omega t, \quad \text{where } K \text{ is a constant}$$

$$\text{and } B'' = K \sin(\omega t + 90^\circ)$$

$$= K \cos \omega t$$

The total pull is proportional to

$$B'^2 + B''^2 = K^2 \sin^2 \omega t + K^2 \cos^2 \omega t = K^2$$

And we see that the pull is constant with time and equal to the maximum value of either core.

In a similar way it may be shown that for polyphase currents in general the lifting powers are constant with time, just as for direct current. This can only be true, however, in a theoretical sense, wherein the resistance of the coil and the magnetic leakage are zero. However, in the practical application these two conditions are sufficiently realized when the armature has been lifted, that is, when there is no appreciable air-gap, so that the tractive force between armature and core is only slightly cyclic.

* D. L. Lindquist, Elec. World, Vol. XLVIII, 1906, p. 128-130.

2. Decrease of Lifting Power Due to Leakage and Air Gap.

- * -

We shall now consider the effect upon the lifting power produced by the introduction of an air-gap into the magnetic circuit. Since the reluctance of air is high as compared with iron the relative reluctance of the complete flux path increases very rapidly at first as the gap widens.

Assume the reactance of the air-gap to be x_s . This will be in the same direction as the electromotive force of self-induction, E , and will be equal to

$$x_s = 2\pi f \frac{0.4 \pi n^2 A}{s} 10^{-8} \text{ ohms} = \frac{\text{const.}}{s} \quad (14)$$

There is at the same time a leakage flux, x , which gives a reactance in phase with x_s . It is made up of two parts, x' and x'' , x' the linked lines in the air space S between the core and coil and of such value that

$$x' = 2\pi f \frac{0.4 \pi n^2}{l k} S 10^{-8} \quad (15)$$

where k , the reluctivity, is equal to unity. x' is constant for a given value of E . The second part of x is

$$x'' = 2\pi f \frac{0.4 \pi n^2}{l k} \frac{D}{3} c 10^{-8} \quad (16)$$

and is the summation of the lines which are linked with the n

turns of the winding. Thus we see from (15) and (16) that

$$x = x' + x'' = 2\pi f \frac{0.4 \pi n^2}{l k} \left(s + \frac{D}{3} C \right) 10^{-8} \quad (17)$$

If we now add x_s and x to r geometrically, as in Figure 2 we get the total impedance Z of one phase. Or,

$$Z = \sqrt{r^2 + (x + x_s)^2} \quad (18)$$

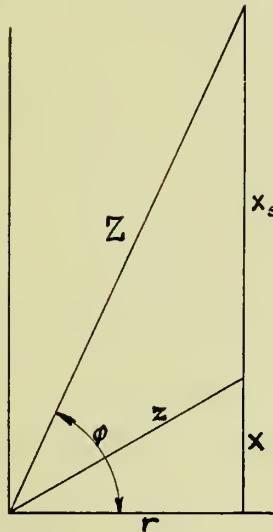


FIG. 2.

Since x_s varies with change of air-gap, s , Z will also be a function of s .

(See curve xy which was plotted between Z and s after having applied a correction to x_s as explained later.)

If, when the armature is in place against the poles, the air-gap were actually zero, the reluctance of the magnetic circuit would be very small indeed,

and the counter electromotive force, E , would be very nearly equal to the impressed electromotive force, E' . That is, there would be only a slight drop of potential in the winding. In this case the maximum induction is

$$B_{0 \text{ max}} = \frac{E' \cdot 10^8}{\sqrt{2} \pi f n A} = \text{const.} \cdot E' \quad (19)$$

Therefore

$$P_0 = \text{const.} \cdot E'^2 \quad (20)$$

However, in every case there remains an air-gap, which, though short, has considerable reluctance, and (19) and (20) will not be exact. But if we now put for the impressed electromotive

force E' the value of the induced, E , the equations will again hold for practical purposes. Then, for any air-gap, s , we may write

$$P_s = \text{const.} \cdot E^2 \quad (21)$$

From the relations

$$E = I \cdot x_s$$

and

$$I = \frac{E'}{Z} = \frac{E'}{\sqrt{r^2 + (x + x_s)^2}}$$

we get

$$E = E' \frac{x_s}{Z}$$

and

$$P_s = \text{const.} \cdot E'^2 \left(\frac{x_s}{Z} \right)^2 \quad (22)$$

Since we have had above, equation (20),

$$P_o = \text{const.} \cdot E'^2$$

we thus see that the relation of the lifting power for any air-gap s to that when it is zero is as follows:

$$\frac{P_s}{P_o} = \left(\frac{x_s}{Z} \right)^2 \quad (23)$$

Equation (22) will give values of P that are too low because x_s is not exact. It will be larger if we correct it for the spreading out of the flux in the air-gap.

We will assume that in the middle of the air-gap the distribution of the flux is uniform across the entire inner section, A' , of the coil. We have already found the value of x' , the flux between the core and the coil, and we know approximately the value of x_s , for the face A . Then the flux of the former path is so related to that of the latter that

$$A_e = A' \frac{x_s}{x_s + x'} \quad (24)$$

where A_e is the effective polar area. Then it is evident that x_s must be increased by the amount $\frac{A_e}{A}$ and we have

$$x_{s \text{ cor}} = x_s \frac{A_e}{A} \quad (25)$$

Putting this value in equation (18) we get a greater impedance and $\cos \phi$; therefore, reduced current and pull.

3. Application of Theory to Calculation of a Magnet.

- * -

Suppose we have given .

E' = the applied p.d. per phase.

f = the frequency,

P = the weight to be lifted, in kg., and

s = the distance through which it is to be pulled.

Let us calculate the required dimensions of a magnet for such service. If we substitute in the equation

$$P = 6.1 B_{\max}^2 A 10^{-8} \text{ kg.}$$

the value of $B_{\max}$ given by

$$B_{\max} = \frac{E_c \cdot 10^8}{\sqrt{2} \pi f n A} \quad (26)$$

where E_c , the induced e.m.f. per phase is

$$E_c = I \cdot x_s$$

and

$$I = \frac{E'}{\sqrt{r^2 + (x + x_s)^2}}$$

and x_s is given by equation (14), we get

$$a(n^2 A)^2 + b(n^2 A)^2 + c = 0 \quad (27)$$

where

$$a = 61.5 \cdot f^2 \cdot P \cdot 10^{-8}$$

$$b = 15.7 \cdot x \cdot f \cdot s \cdot P - 19.1 \cdot E'^2 \quad (28)$$

and $c = P \cdot Z^2 \cdot s \cdot 10^8$

Solving these equations gives $(n^2 A)$, which is the product of the two factors most needed in designing the magnet. But from equation (26) we see that

$$n A = \frac{E' \cdot 10^8}{\sqrt{2} \pi f B_{O \max}} \quad (29)$$

Dividing the solution of (27) by (29) gives the desired quantity, n . The value of A is then, of course, determined also, and the problem is practically solved. There then remains merely the determining of the size of the wire needed, and the amount of space to be provided to contain the coils.

In this investigation we have neglected to consider the effect of hysteresis and eddy current losses, temperature, the vibration of the armature, etc., upon the amount of load lifted. That they all decrease the effective pull is evident, but considering the fact that the iron used was good transformer iron, well coated with shellac to prevent eddy currents, that the spool was constructed in such a way as to prevent eddy currents in it, and that the magnet was not kept in the circuit at any one time long enough to cause rise of temperature above 50°C , it has been assumed that these combined effects are negligible in comparison with those discussed.

PRELIMINARY EXPERIMENTS.

- * -

B-H Curve of Iron used in Core.

- - * - -

In order to have a definite idea concerning the nature of the iron used in the magnetic path, a preliminary test was made in which the B-H curve, number 1, page 19, was found. The customary ring method of determination was employed, that is, Rowland's Ballistic Method, using direct current. This information was of service further in making calculations for the theoretical value of the lifting power of the direct current magnet. (See page 33.)

The values of B thus derived do not agree exactly with the values computed by means of the equation*

$$P = 4.07 \cdot B^2 \cdot A \cdot 10^{-8}$$

which, we have seen, represents the pull in terms of B and the cross-sectional area, A. In other words the ordinates of curve Number 1 are too low in every case. A. Hoyt Taylor has shown** that this is due to a defect of the step by step method of determining the B-H curve, and suggests a way of finding it exactly.

* See page 5.

** Phys. Rev., Vol. XXIII, Aug. 1906. p. 95.

This method, however, was not called to the notice of the author until too late to employ it in this work. It is possible that the maximum induction is much higher, then, than 11,000 as given by our curve. According to tables for transformer iron, saturation is placed at about 20,000. The shape of curve Number 1 suggests that the saturation point was almost reached, and consequently not much dependence was placed on the accuracy of our curve, except for information it gives by its form rather than by the numerical value of the ordinates.

Referring to curve Number 1 it will be seen that we have at 4 amperes excitation 85.7% saturation, as given by the formula*

$$\% \text{ of saturation} = \frac{ob}{na}$$

where ob is the intercept on the y-axis of a tangent at the point a considered.

* H. S. Baker, Elec. World and Eng., Vol. XLVI, 1905, p. 1037.

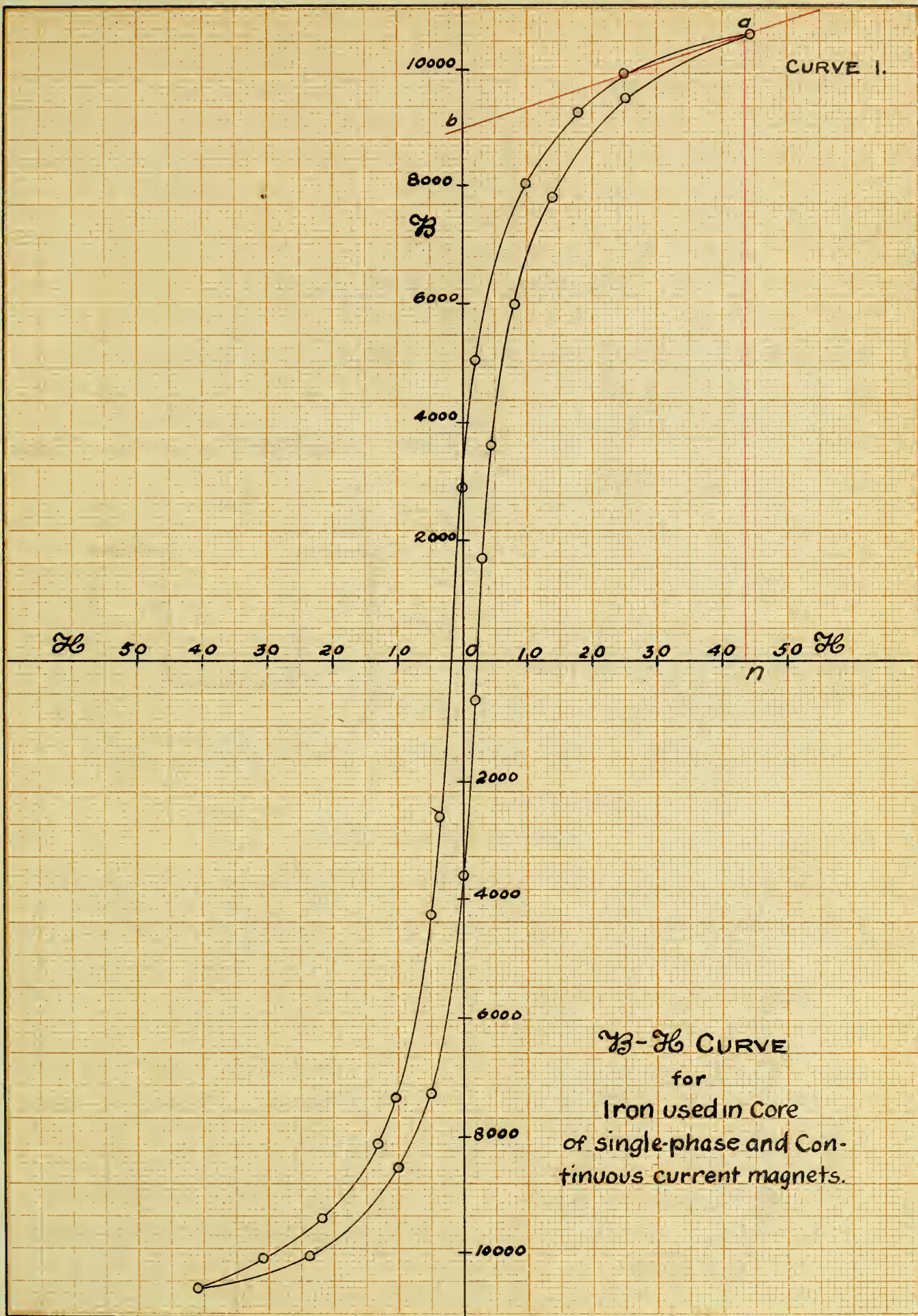
Data for Preliminary Experiment.

- * -

I	d	d	H	B
0.09	38	38	1.01	406
0.17	95	133	1.904	1420
0.22	68	201	2.464	2160
0.28	58	259	3.136	2770
0.43	128	387	4.816	4140
0.50	41	428	5.600	4580
0.58	52	480	6.496	5130
0.71	67	547	7.952	5870
0.90	77	624	10.080	6680
1.18	81	705	13.220	7540
1.80	+118	+823	20.160	8820
3.30	+122	+945	36.960	10130
1.85	- 70	+875	20.72	9350
1.18	- 70	+805	13.22	8630
0.91	41	+764	10.19	8180
0.71	50	714	7.952	7640
0.58	43	671	6.496	7180
0.50	32	639	5.600	6840
0.43	25	614	4.816	6580
0.25	95	519	2.800	5540
+0.18	50	469	2.02	5020
+0.12	53	416	1.41	4460
+0.07	63	+353	0.784	+3780
0.00	107	+246	0.00	+2630
-0.07	111	+135	-0.784	+1440
-0.15	140	- 5	-1.570	- 54
0.20	118	-123	2.240	-1320
0.29	123	246	3.244	2630
0.43	154	400	4.816	4280
0.50	52	452	5.60	4840
0.57	60	512	6.384	5400
0.71	77	589	7.952	6300
0.82	49	638	9.184	6840
0.95	52	690	10.64	7380
1.20	70	760	13.46	8130
1.87	117	877	20.95	9400
2.22	40	917	24.86	9830
2.78	-43	960	31.14	10270
3.70	-47	1007	41.44	10780

I	d	d	H	B
2.77	+31	976	31.03	10430
2.20	+28	948	24.64	10140
1.58	49	899	17.70	9630
1.18	47	852	13.22	9130
0.92	49	803	10.30	8580
0.71	50	-753	7.952	8060
0.58	41	-712	6.496	7610
0.50	+32	-680	5.6	7280
0.43	25	655	4.816	7000
0.23	114	541	2.576	5800
0.17	47	494	1.904	5270
0.12	41	453	1.344	4860
0.07	61	392	-0.784	4190
0.00	+104	-286	0.00	-3060
+0.07	+118	-168	+0.784	-1800
0.12	105	+ 63	1.344	- 670
0.17	89	+ 26	1.904	+ 280
0.25	131	157	2.800	+1680
0.40	175	332	4.480	3560
0.43	30	362	4.816	3870
0.50	52	414	5.800	4440
0.58	61	475	6.496	5080
0.72	77	552	8.064	5930
0.91	85	637	10.19	6820
1.22	90	727	13.66	7780
1.62	81	808	18.15	8640
2.30	+79	887	25.76	9500
3.93	+92	979	44.02	10440
2.27	-65	914	25.42	9770
1.65	-47	867	18.48	9270
1.21	51	816	13.56	8740
0.90	55	761	10.08	8150
0.72	46	715	8.064	7650
0.58	41	674	6.496	7230
0.50	32	642	5.80	6880
0.43	25	617	4.816	6620
0.33	52	565	3.696	6050
0.23	57	508	2.576	5430
+0.15	58	450	1.570	4820
+0.08	67	383	0.896	4110
0.00	132	251	0.000	2680

I	d	d	H	B
-0.07	118	+133	0.784	+1410
-0.12	116	+ 17	1.384	+ 180
0.17	88	- 71	1.904	- 760
0.23	100	-171	2.576	-1830
0.29	80	251	3.248	2780
0.43	155	406	4.816	4340
0.50	51	457	5.6	4880
0.58	62	519	6.496	5560
0.71	76	595	7.952	6370
0.92	87	682	10.3	7310
1.22	90	772	13.66	8230
1.60	74	846	17.92	9070
2.28	- 78	924	25.54	9880
4.02	-101	1025	45.02	10870
2.28	+ 67	958	25.54	10250
1.57	+ 68	890	17.70	9520
1.22	41	849	13.66	9080
0.91	53	796	10.19	8520
0.72	49	747	8.064	8000
0.58	40	707	6.496	7560
0.50	31	676	5.6	7240
0.43	25	651	4.816	6960
0.29	72	579	3.244	6190
0.21	55	524	2.352	5620
0.14	55	469	1.568	5020
0.10	33	436	1.12	4660
0.07	43	393	0.784	4220
0.00	105	288	0.00	3080



DESCRIPTION OF APPARATUS.

- * -

The magnets used in this work were of the laminated core type, the punchings being of the shape and dimensions shown in Figure 3, cut from transformer-iron stock $1/64$ " gauge. Before as-

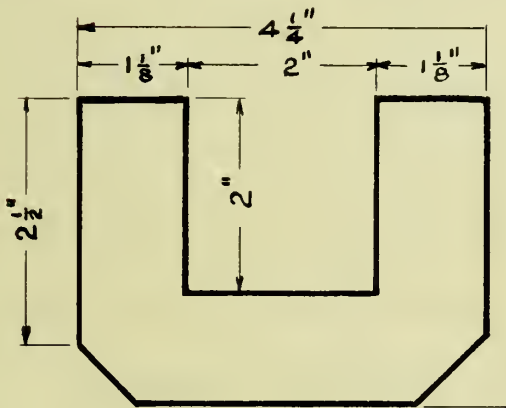


FIG. 3.

sembling, each lamina was given a coat of shellac; and after the assembled core was riveted together all faces were filed smooth.

For the single-phase magnet two simple U-shaped cores were constructed, each 1" thick, of which the outer sheets were of $1/16$ " stock to give stiffness. With the open ends

of these placed together as in Figure 4 the completed core was ready for the energizing coils, which were wound on slotted brass spools of such size as would fit closely on the long arms of the core, allowing a few turns of oiled linen between for insulation.

The coils, two in number, were wound with 173 turns each of Number 14 copper

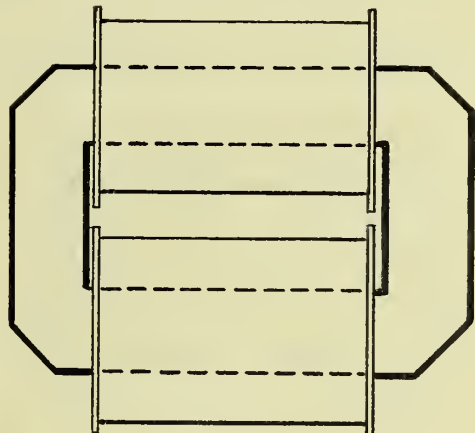


FIG. 4.

magnet wire. A terminal was brought out after the first 131 turns for varying the current through the coils.

For the study of the properties of the magnet when energized with direct current the same core and coils were used. For the three-phase current tests a three pole core was built up of the same kind of laminations as before.

In order to procure the desired shape it was necessary to cut one punching of each layer into the form shown in Figure 5. Then it is seen that the part shown in Figure 6 could easily be built up, the dotted

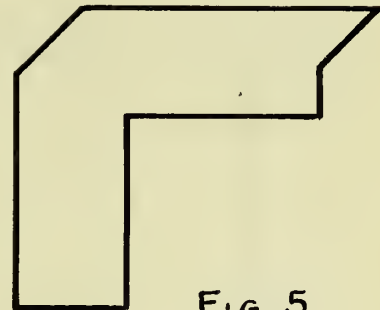


FIG. 5.

line showing how the cut piece of Figure 5 was fitted to one of the whole punchings. In alternate layers the positions of these two parts, A and B, Figure 6, were interchanged, so that in the finished core the whole mass was firmly interlaced and rigid.

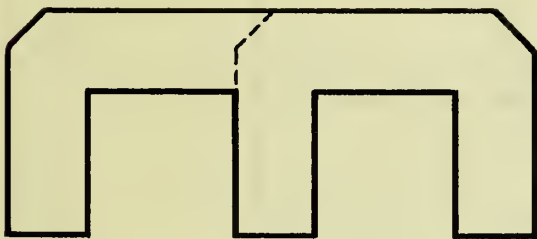


FIG. 6.

Two parts were constructed as above described and being placed together as in Figure 7 formed the flux path for the three-phase magnet. The two coils of the previously described apparatus, together with a third which was made in a similar manner, were used to excite this core, being mounted as indicated by dotted lines in Fig-

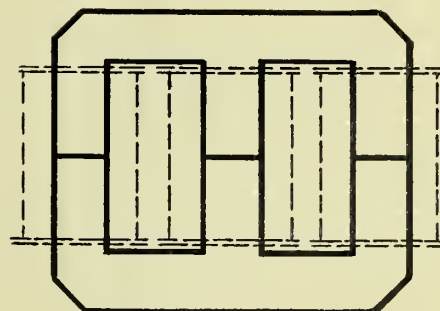


FIG. 7.

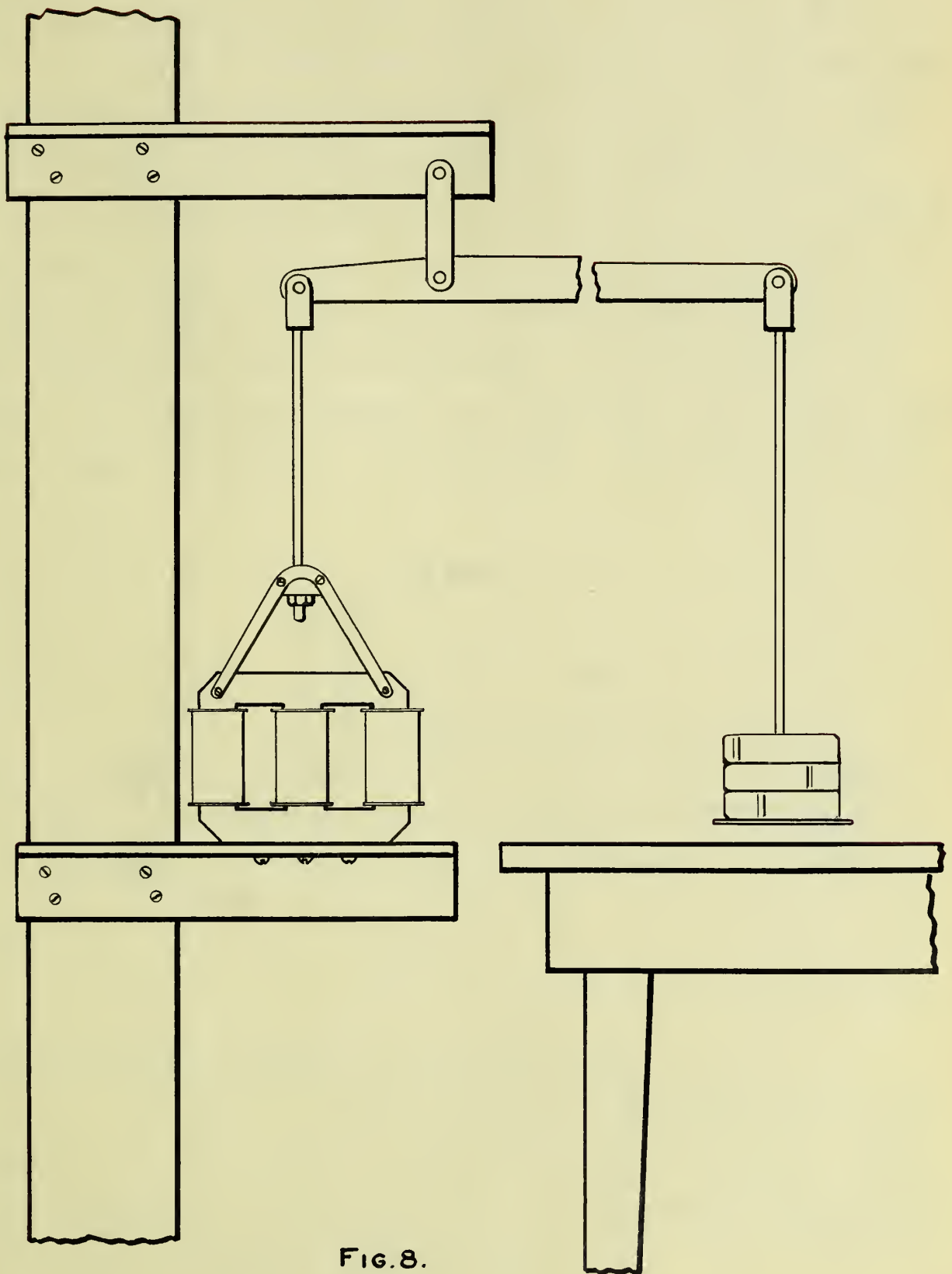
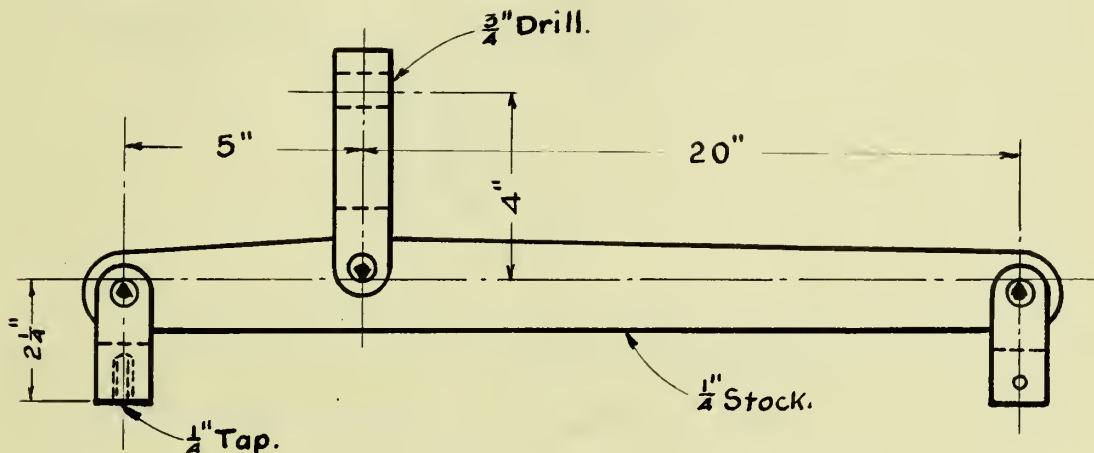


FIG. 8.

ure 7. The source of energy was the three-phase end of a four pole motor-generator set, rated to run at from 1200 to 1800 R. P. M.

Energy for excitation with single-phase current was taken from one phase of a two-phase, 110 volt, 60 cycle system. For direct current tests energy was taken from storage batteries.

The general arrangement of the set-up is shown in Figure 8. Two 3" angle-irons were bolted in a horizontal position to the flange of a vertical I-beam post, one on the level of the table and the other some three feet above it. To the lower one the frame of the magnet was bolted and to the upper one, the lever system by which the pull was to be measured. This lever is shown in



detail in Figure 9 which is self explanatory.

"Air-gaps" of various dimensions were maintained by the insertion of small plates of brass of suitable thickness. They were of approximately the same size as the pole-face itself, and were of the thicknesses shown in table I.



DESCRIPTION OF METHOD.

- * -

For the experiments using single-phase current the electrical connections were made as shown diagrammatically in Figure 10; the two coils, B and C, were connected in series. In the figure

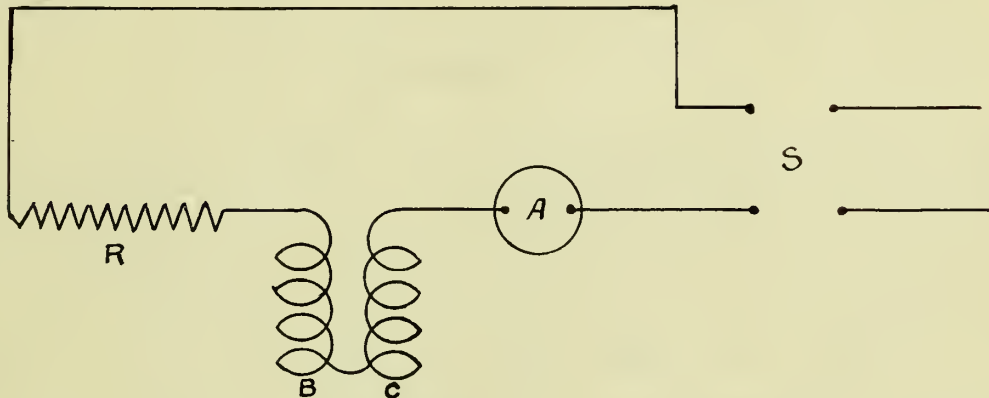


FIG. 10.

A is an alternating current ammeter, 0-10 amperes, R is a non-inductive resistance for current regulation, and S is a double pole switch.

The three coils, A, B, and C, of the three-phase magnet were connected in Y, as shown by Figure 11. The current was furnished by the motor-generator through the three-pole switch S; an ammeter M was placed in one phase only, since the three were well balanced. At first an ammeter was placed in each phase, and the three were balanced by adding a few turns to the coil through which

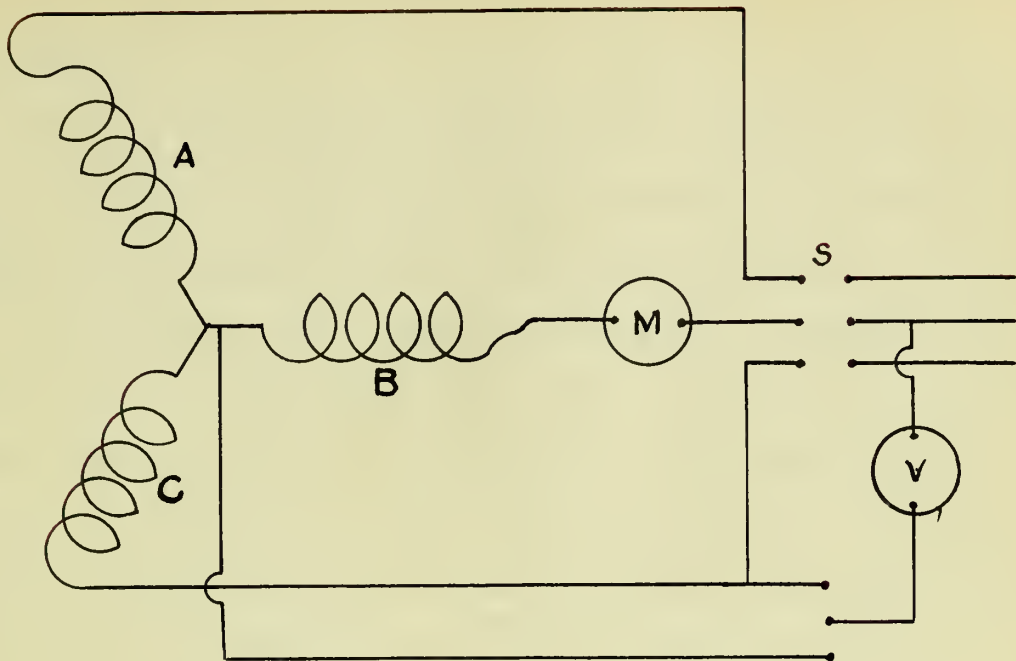


FIG. 11.

the largest current flowed. The increased inductance per phase due to these extra turns is surprisingly noticeable, and but one or two turns were necessary. The voltmeter, V, was arranged to show the potential between one pair of mains when S was open or closed, and also the potential across one coil by connecting as shown by the broken line.

The measurement of the attractive force of the poles was an easy and comparatively exact process when continuous current excitation was employed. The brass plate or plates giving the desired amount of "air-gap" were inserted, the armature was lowered into place, and the circuit was closed. After adjusting the resistance in series with the coil until the desired amount of current flowed, weights were placed on the opposite end of the lever until the attractive force was overcome. The last few weights added were of small denomination, so that a fairly high degree of accu-

racy was obtained.

With the alternating current tests, however, the chattering of the cores due to any slight variation from perfect balance of the three phases proved to be a source of difficulty in taking readings. Although we have seen that the pull is constant with time, yet it will be remembered that such is true only for perfectly balanced, ideal systems. If there be a point in any cycle that has a weaker or stronger pull than the average value, this irregularity will be cyclic; and if it recurs at just the proper frequency, vibrations of such intensity may be set up in the system as will overcome the attraction of the armature, letting it drop sooner than it would were the irregularities not present.

The short arm of the beam used was weighted in order to balance the weight of the long arm. Adjustment was so made that the system, though rather heavy, would respond to the addition of two grams on the long arm, the magnets not being excited.

DISCUSSION OF RESULTS.

- * -

The results of this experiment apparently disprove the original assumption that the lifting-power of single-phase, continuous and three-phase current magnets are as 1 : 2 : 3. However if we consider all modifying factors the results agree with the theoretical conclusions sufficiently well to confirm their accuracy.

The most important source of error in taking data was that already mentioned on page 14, where values of B for^{the} continuous current magnet were in reality much higher than the values computed. If an error is made in finding B the calculated value of P will be quite noticeably in error since P varies as B^2 . So that when curves I, VI, and XI are compared, account must be taken of the fact that the three are not plotted under conditions of equal maximum induction. If points are taken on these curves where $B_{\max}$ has the same value for each, the pull for the three-phase electro-magnet at once has a higher value than that of the single-phase or continuous current magnet. But the ratio has not quite the value of 3 : 1 : 2 respectively, owing to other conditions which will be mentioned later.

If we apply formulae (8) and (19) we get

For 10 amperes continuous current, $B_o \max = 22000$ about.

For 10 amperes single-phase current, $B_o \max = 15000$, about.

For 10 amperes three-phase current, $B_o \max = 10000$, about.

Referring again to Curves I, VI, and XI which show the pull obtained for the three by actual test, it is seen that for equal values of effective current the continuous current gives the maximum pull. This is exactly what should occur, considering the relative values of B in the three cases.

The effect of heating, if it is not carried to a degree that seriously affects the permeability of the iron or that is sufficient to injure the insulation, is not so objectionable as would at first be imagined. The resistance, r , increases with the temperature, thus increasing the power factor (See Figure 2, page 9). The eddy currents decrease with rise of temperature, and the current and total losses also.

It is not the heating due to I^2R losses, however, that concerns the designer. This can be obviated by simply using larger wire. But the heating due to the hysteresis loss of the core, since it varies as $B^{1.6}$ and as f^2 , can be controlled practically only by using the proper value of B . Since the pull varies as B^2 , we should take B as high as possible, therefore, as is compatible with cool operation.

It will be noticed from the curves which show the variation of pull with change of air-gap (Curves IV, IX, and XII) as found for the three forms of current, that the range over which a fairly high value of P is secured is greatest for three-phase excitation. For certain uses this is an important property. Since the leakage reactance decreases as the air-gap increases (See curve for x_s cor, curve XV) it is evident that with constant impressed electromotive force there will be an increase of current, which

results in the flattening of the pull-air-gap curve. In reality, this reaches to a considerable value under favorable conditions; and since the power factor increases also with air-gap the effect is very desirable. After the load is lifted the reactance chokes down the current to a quite low value, if the pole faces fit very close together.

Curves IV and V show that the decrease of lifting power of the continuous current magnet is very abrupt, when the air-gap is introduced, even if it is only a few millimeters in length. These curves, it will be noted, are steeper than the corresponding ones for the three-phase current, even though the abscissae for the continuous current curves have been multiplied. Curves IX and X indicate that for single-phase currents a similar decrease occurs, which, however, is not quite so abrupt as in the case of the continuous current.

Aside from the difficulty of getting exact values for B, the most important cause of the variation of the ratio of the lifting powers from that assumed, 1 : 2 : 3, is the air-gap reactance. This increases quite rapidly as the air-gap is reduced, causing a simultaneous decrease in the power factor, $\cos \phi$, (Curve XV). It is evident that any cause which reduces the attractive force for the three-phase or single-phase current electromagnet will, to some extent affect the ratio of this force to the unvariable pull produced by a continuous current magnet.

SUMMARY.

- * -

The working out of the foregoing therefore shows that:-

1.) The lifting powers, under equal maximum induction, for single-phase, direct current, and three-phase current magnets, vary as $1 : 2 : 3$; but that for these relations to exist

2.) The resistance of the winding must be very nearly zero and the effects of hysteresis loss, leakage and reactance must be negligible, for the alternating current magnets.

3.) In practical operation, since the conditions as set down in 2.) can never be fully realized, the pull of the three-phase magnet, though greater than that of either the continuous current or single-phase apparatus, will not be as much greater as is claimed in the thoery of Liska.

- - * - -

This thesis was prepared under the direction of Professor A. P. Carman, head of the Department of Physics, in the laboratory of the University of Illinois.

The theory given is in large part taken from the various references cited below.

D A T A .

- * -

Constants of Magnet Used.

- - * - -

$A = 6.45 \text{ cm}^2$ = cross-sectional area of one pole.

Mean length of magnetic circuit, with air-gap reduced to minimum, 38.8 cm.

Minimum length (average) of air-gap, 0.021 cm. (see curve XIV)

Total number of turns per phase, $n = 173$.

Resistance of winding, per phase, $R = 0.2135$ ohms.

Frequency of three-phase current, $f = 50$.

Frequency of single-phase current, $f = 60$.

Thickness of plates used as air-gaps, Table I.

Table I.

- * -

Plates Used for "Air Gaps".

No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
0.28 mm	0.85 mm	1.61 mm	2.38 mm	4.75 mm	9.75 mm
.28	.85	.62	.37	.75	.77
.28	.86	.62	.37	.76	.63
.29	.85	.61	.37	.75	.65
.28	.86	.62	.37	.74	.77
.28	.84	.61	.37	.74	.54
.29	.83	.61	.38	.74	.72
.28	.84	.61	.37	.74	.74
.28	.85	.61	.38	.74	.60
.29	.84	.61	.37	.74	.67
0.283	0.847	1.613	2.373	4.745	9.684

CONTINUOUS CURRENT.

- * -

Table II.

- * -

I = Current in Amperes	Attractive Force in Kg. for various Air-gaps and Currents				
	0	.0283 cm	.0566 cm	.0849 cm	.1413 cm
0.5	23.2	-	-	-	-
1.0	47.0	10.5	3.0	-	.8
2.0	76.3	33.2	13.0	9.2	3.4
3.0	90.5	57.6	27.0	17.6	7.8
4.0	98.3	73.3	42.4	29.6	13.6
5.0	107.7	84.7	53.4	42.4	19.4
6.0	112.1	92.1	66.3	55.4	27.6
7.0	116.5	99.1	76.1	63.6	35.6
8.0	122.0	102.0	83.1	72.2	45.8
9.0	127.6	106.3	89.7	76.5	49.3
10.0	132.2	-	94.7	80.1	55.8

Table III.

- * -

I	Attractive Force in Kg. for various Air-gaps and Currents				
	.2179 cm	.2939 cm	.4552 cm	.5331 cm	.7684 cm
1.0	.5	.28	.16	.16	.12
2.0	1.8	.96	.56	.52	.28
3.0	3.9	2.08	1.16	1.00	.56
4.0	7.2	3.80	2.12	1.60	.92
5.0	11.0	6.00	3.28	2.48	1.40
6.0	15.7	8.36	4.48	3.56	2.04
7.0	20.8	11.44	6.20	4.68	2.72
8.0	25.8	14.80	7.80	6.28	3.56
9.0	32.0	18.80	9.76	7.60	4.40

Table IV.

- * -

I	Attractive Force in Kg. for various Air-gaps and Currents		
	0.9684 cm	1.206 cm	1.68 cm
1.0	.20	.16	.12
2.0	.36	.24	.16
3.0	.48	.36	.26
4.0	.80	.56	.33
5.0	1.16	.80	.52
6.0	1.56	1.12	.64
7.0	2.00	1.48	.84
8.0	2.60	1.84	1.08
9.0	3.16	2.28	1.28
10.0	3.88	2.76	1.56

Single-Phase 60 cycles.

- - * - -

Table V.

- -

I	Attractive Force in Kg. for Air-gaps in cm.						
	s = 0	.0283	.0566	.0849	.1413	.2189	.2939
1.0	13.27	6.48	3.28	1.76	.96	.48	.28
2.0	25.48	15.00	8.77	5.72	3.32	1.28	1.04
3.0	31.02	23.21	15.80	11.27	6.12	3.48	2.36
4.0	37.31	29.55	21.48	16.20	10.77	5.92	4.00
5.0	40.53	33.66	27.48	22.28	14.95	8.36	5.68
6.0	44.26	38.27	31.02	25.25	16.60	10.87	7.68
7.0	50.50	40.53	35.74	31.02	23.21	14.60	9.97
8.0	50.15	44.26	38.24	-	25.48	18.12	13.60
9.0	49.42	45.91	38.38	31.22	29.44	19.55	14.49
10.0	-	-	46.30	-	29.74	25.76	19.10

Table VI.

- * -

I	Attractive Force in Kg. for Air-gaps in cm.					
	s = .4552	.5311	..6924	.9684	1.2057	1.6802
1	.20	.16	.12	.11	.08	.072
2	.52	.40	.36	.24	.16	.12
3	1.16	.88	.68	.40	.28	.18
4	1.96	1.52	1.16	.64	.44	.28
5	3.00	2.36	1.76	1.00	.66	.40
6	4.28	3.24	2.20	1.40	.92	.56
7	5.60	4.44	2.96	1.62	1.32	.76
8	8.60	5.68	3.80	2.44	1.64	.96
9	-	6.56	-	2.92	2.04	1.20
10	11.27	8.12	5.28	3.56	2.48	1.40

THREE PHASE CURRENT EXCITATION - 50 CYCLES.

- * -

In the next eight tables various values of e.m.f. are given which have the following significance:-

E'' = line voltage across one pair of mains, no current in magnet, as read by voltmeter. See Figure 12.

E' = applied potential for one phase = $E''/\sqrt{3}$

E = voltage across one pair of mains, with magnet excited, read by voltmeter.

E_v = voltage across one phase, read by voltmeter.

E_c = voltage across one phase = $E/\sqrt{3}$

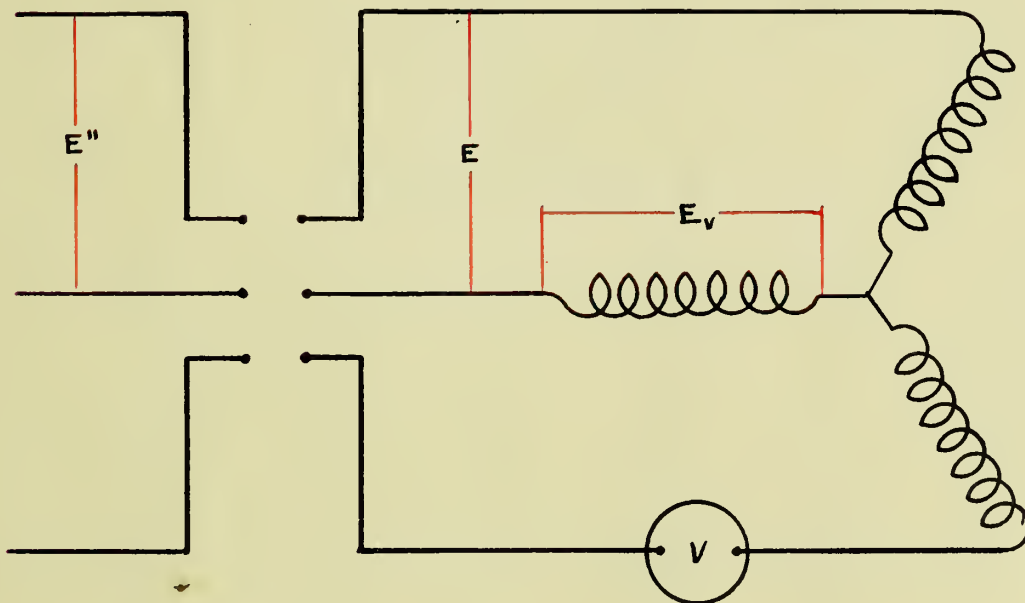


FIG. 12.

Table VII.

- * -

Air-gap = 0.

Amp.	E"	E'	E	E _v	E _c	P in kg.
1	43.2	24.9	40.0	22.7	23.11	21.88
2	62.5	36.1	55.7	31.5	32.1	39.04
3	76.3	44.2	64.6	36.7	37.3	50.40
4	84.5	48.7	69.4	40.0	40.2	57.
5	91.3	52.8	73.0	42.1	42.3	65.74
6	96.2	55.7	75.3	43.5	43.6	70.34
7	101.7	58.6	77.7	45.2	44.9	73.14
8	106.8	61.7	80.2	46.5	46.3	77.74
9	111.3	64.1	81.8	47.6	47.2	85.74
10	116.0	66.9	83.6	48.7	48.3	86.94

Table VIII.

- * -

Air-gap = .0566 cm.

Amp.	E"	E'	E	E _v	E _c	P in kg.
1	24.4	14.1	20.0	12.0	11.6	4.6
2	41.8	24.2	34.2	19.5	19.7	12.0
3	59.3	34.3	47.3	27.1	27.3	21.4
4	70.5	40.7	55.7	31.7	32.1	28.0
5	81.7	47.2	63.0	36.3	36.4	34.4
6	89.7	51.8	67.4	38.7	38.8	42.4
7	96.0	55.4	70.8	40.7	41.5	44.2
8	101.6	58.6	73.8	42.5	42.6	51.0
9	107.3	61.8	76.4	43.9	44.2	55.6
10	112.6	65.1	78.8	45.6	45.6	60.2

Table IX.

- * -

Air-gap = .2179 cm.

Amp.	E"	E'	E E	E _V	E _C	P in Kg.
2	23.1	13.4	15.4	8.0	8.9	2.4
3	34.6	20.0	22.7	12.6	13.1	4.8
4	45.7	26.4	30.1	17.0	17.4	8.0
5	57.1	33.0	37.2	21.3	21.5	12.0
6	67.3	38.9	43.8	25.0	25.4	15.4
7	76.0	43.9	49.4	28.0	28.6	18.4
8	84.4	48.8	53.7	30.7	30.9	23.6
9	93.0	53.8	59.3	33.7	34.3	26.4
10	100.2	57.8	61.4	34.7	35.4	29.8

Table X.

- * -

Air-gap = .5331 cm.

Amp.	E"	E'	E E	E _V	E _C	P in Kg.
3	25.3	14.6	14.0	8.0	8.1	2.8
4	34.0	19.6	18.0	10.	10.4	3.4
5	42.7	24.7	22.8	13.	13.2	4.8
6	50.7	29.3	27.0	15.5	15.6	6.0
7	59.3	34.3	31.5	18.0	18.2	7.8
8	66.5	38.4	35.3	20.1	20.4	9.2
9	74.6	43.1	39.7	22.7	22.8	11.6
10	80.7	46.7	43.2	24.8	24.9	14.0

Table XI.

- * -

Air-gap = .6924 cm.

Amp.	E"	E'	$\bar{E}_V$	E_C	E_C	P in kg.
3	22.8	13.2	12.8	6.	7.4	1.68
4	31.4	18.2	15.5	8.	8.9	2.56
5	39.0	22.6	19.0	10.8	10.9	3.32
6	46.3	26.8	22.7	13.0	13.2	4.28
7	54.0	31.2	26.4	15.3	15.3	5.60
8	61.6	35.6	30.2	17.5	17.4	6.88
9	68.4	39.6	33.5	19.3	19.3	8.40
10	76.6	44.2	37.2	21.4	21.4	10.40

Table XII.

- * -

Air-gap = .9684 cm.

Amp.	E"	E'	E	E_V	E_C	P in Kg.
3.3	222.7	13.2	10.	5.	5.8	1.56
4.5	31.8	18.4	13.5	7.	7.8	1.92
5.0	34.7	20.0	15.0	8.5	8.7	2.16
6.0	41.6	24.0	17.5	10.2	10.1	2.68
7.0	48.8	28.3	20.6	12.0	11.9	3.36
8.0	54.8	31.6	23.3	13.0	13.5	4.00
9.0	61.5	35.6	26.3	15.0	15.2	4.80
10.0	67.8	39.2	28.7	16.5	16.2	5.60

Table XIII.

- * -

Air-gap = 1.2057 cm.

Amp.	E"	E'	E	E _v	E _c	P in kg.
4	25.0	14.4	9.5	5.	5.5	.80
5	32.6	18.8	13.0	7.	7.5	1.20
6	39.5	22.8	15.5	8.	8.9	1.60
7	46.3	26.7	18.3	10.	10.6	2.40
8	53.2	30.7	20.7	12.	11.9	3.00
9	58.7	33.9	23.0	13.	13.3	3.60
10	66.0	38.2	25.8	14.5	14.9	4.20

Table XIV.

- * -

Air-gap = 1.6802 cm.

Amp.	E"	E'	E	E _v	E _c	P in kg.
4	24.0	13.9	8.	4.	4.6	.48
5	31.8	18.4	10.5	5.	6.1	.68
6	36.8	21.3	13.	7.	7.5	.96
7	42.8	24.7	15.	8.	8.7	1.32
8	48.7	28.2	17.0	9.	9.8	1.36
9	55.5	32.1	19.0	10.5	11.0	1.76
10	61.0	35.3	21.5	12.0	12.4	2.16

Table XV.

- * -

Calculated values of P for various air-gaps, at various values of applied electromotive force.

s in cm.	$\frac{A}{A_e} \left(\frac{x_s \text{ cor}}{Z} \right)^2$	E'=10	20	30	40	50	60	70
0.0566	.712	4.57	18.8	41.4	73.4	114.7	105.5	225
0.2179	.691	4.42	17.6	39.7	70.6	111.3	158.7	217
0.5331	.649	4.17	16.6	37.5	66.7	104.3	150.0	204
0.6924	.632	4.07	15.6	36.6	64.9	101.4	146.1	198
0.9684	.577	3.72	14.8	33.3	59.4	92.7	133.3	181
1.2057	.552	3.44	13.8	31.0	55.0	86.1	129.0	169
1.6802	.488	3.15	12.6	28.3	50.4	78.7	113.0	154

Table XVI.

- * -

s = length of air-gap in cm.

x_s = reactance of air-gap.

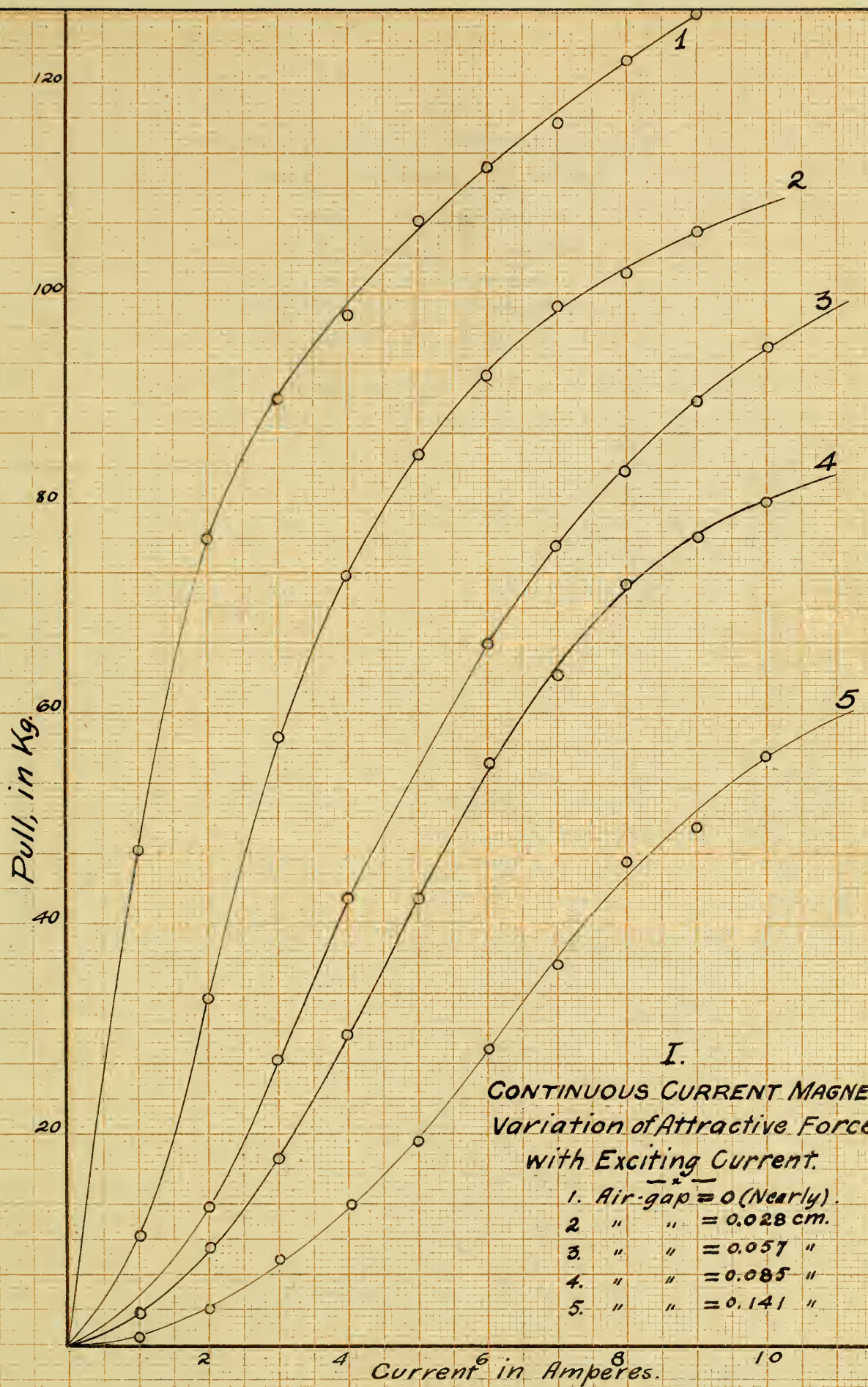
A_e = effective area of pole face = $A' \frac{x_s}{x_s + x'}$

$x_s \text{ cor}$ = corrected value of x_s and is equal to $x_s \frac{A_e}{A}$

$Z = \sqrt{r^2 + (x_s \text{ cor} + x)^2}$ = the total impedance of one phase.

The last two columns are factors that occur frequently in the calculations. (See page

s	x_s	A_e	$x_s \text{ cor}$	Z	$\cos \phi$	$(\frac{x_s \text{ cor}}{Z})^2$	$\frac{A}{A_e} (\frac{x_s \text{ cor}}{Z})^2$
0.0283	27.05	8.986	37.84	37.93	.006	.995	.716
0.0566	13.52	8.974	18.78	18.87	.012	.991	.712
0.0849	9.02	8.965	12.55	12.64	.018	.987	.707
0.1413	5.42	8.955	7.53	7.62	.030	.980	.701
0.2179	3.51	8.914	4.88	4.97	.046	.967	.691
0.2939	2.60	8.891	3.59	3.68	.063	.953	.681
0.4552	1.68	8.839	2.30	2.39	.096	.926	.663
0.5311	1.44	8.812	1.97	2.07	.111	.906	.694
0.6924	1.11	8.758	1.51	1.61	.143	.881	.632
0.9684	.79	8.665	1.06	1.18	.195	.808	.577
1.2057	.634	8.575	.843	0.960	.238	.770	.552
1.6802	.455	8.443	.594	0.721	.319	.681	.488



II

CONTINUOUS CURRENT MAGNET

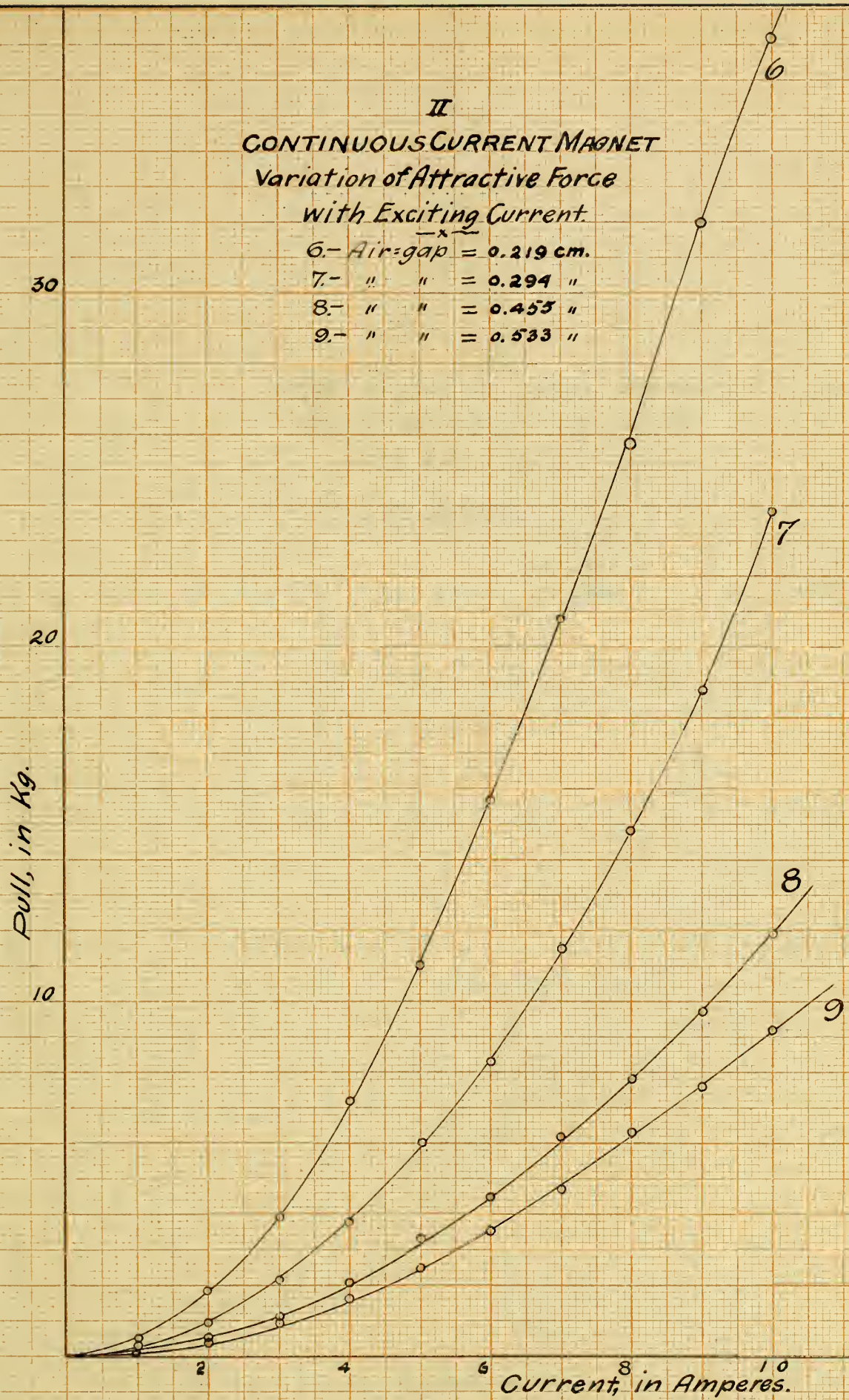
Variation of Attractive Force
with Exciting Current

6.- Air-gap = 0.219 cm.

7.- " " = 0.294 "

8.- " " = 0.455 "

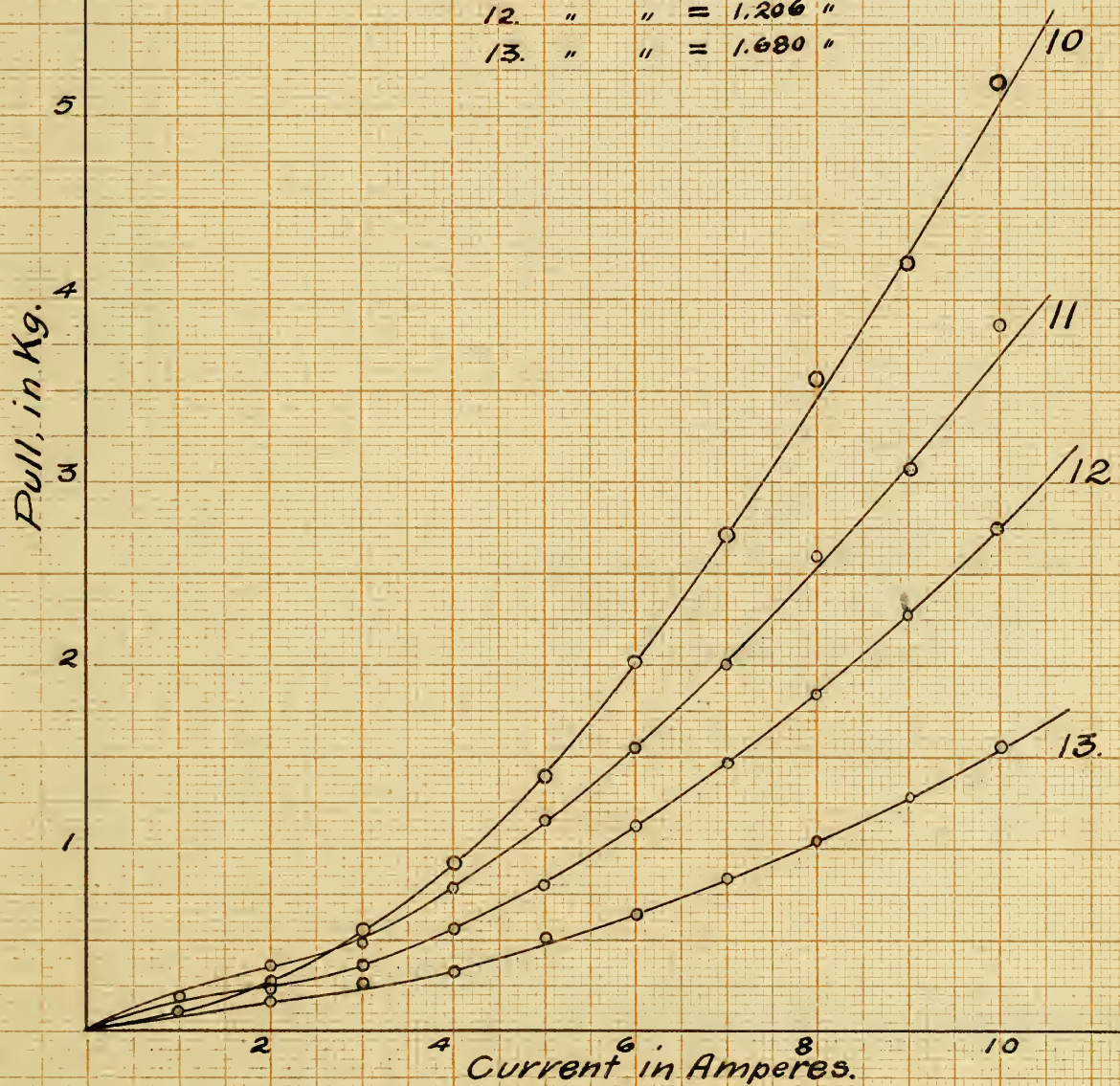
9.- " " = 0.533 "



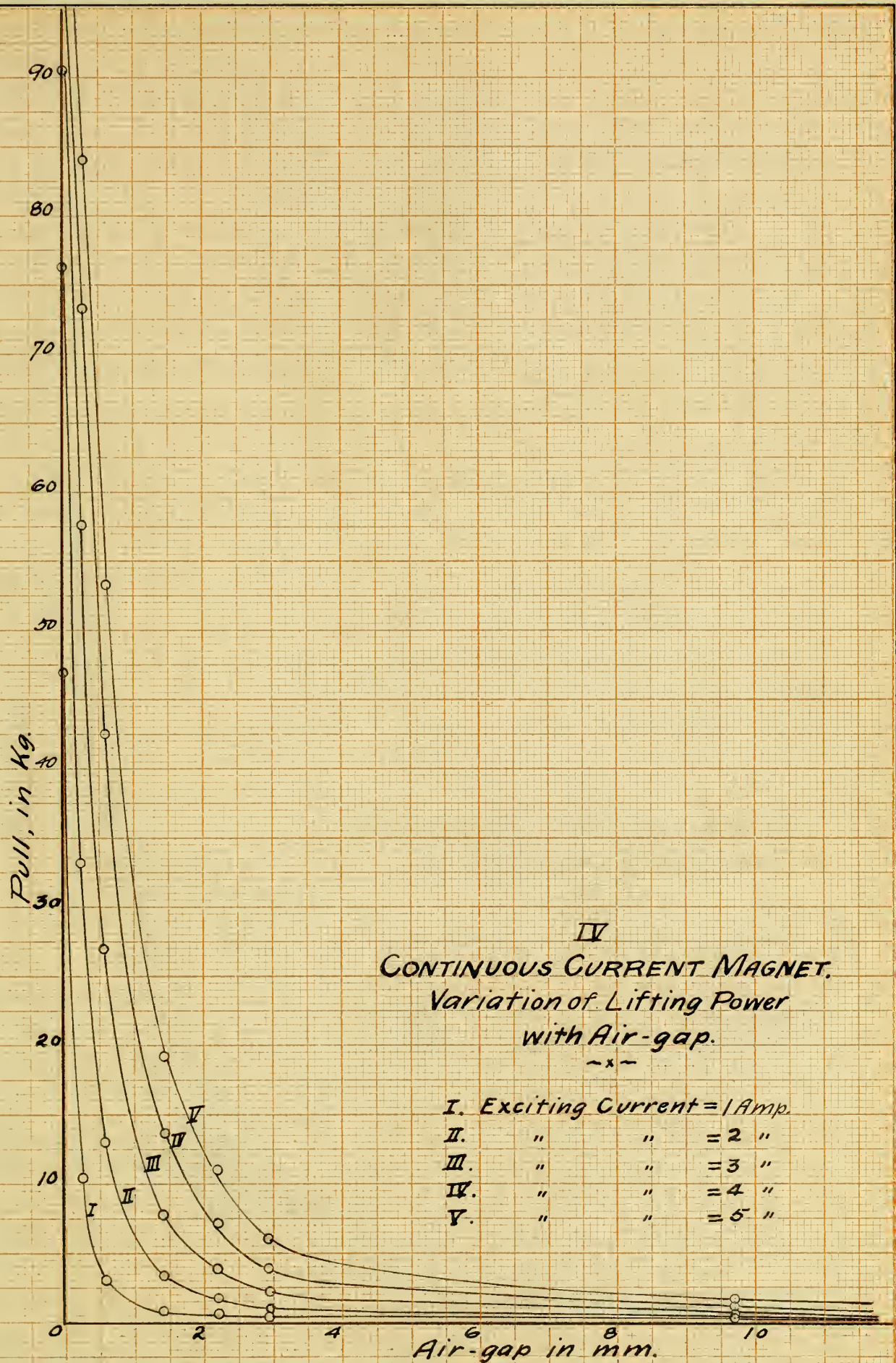
III.
CONTINUOUS CURRENT MAGNET.
Variation of Attractive Force
with Exciting Current.

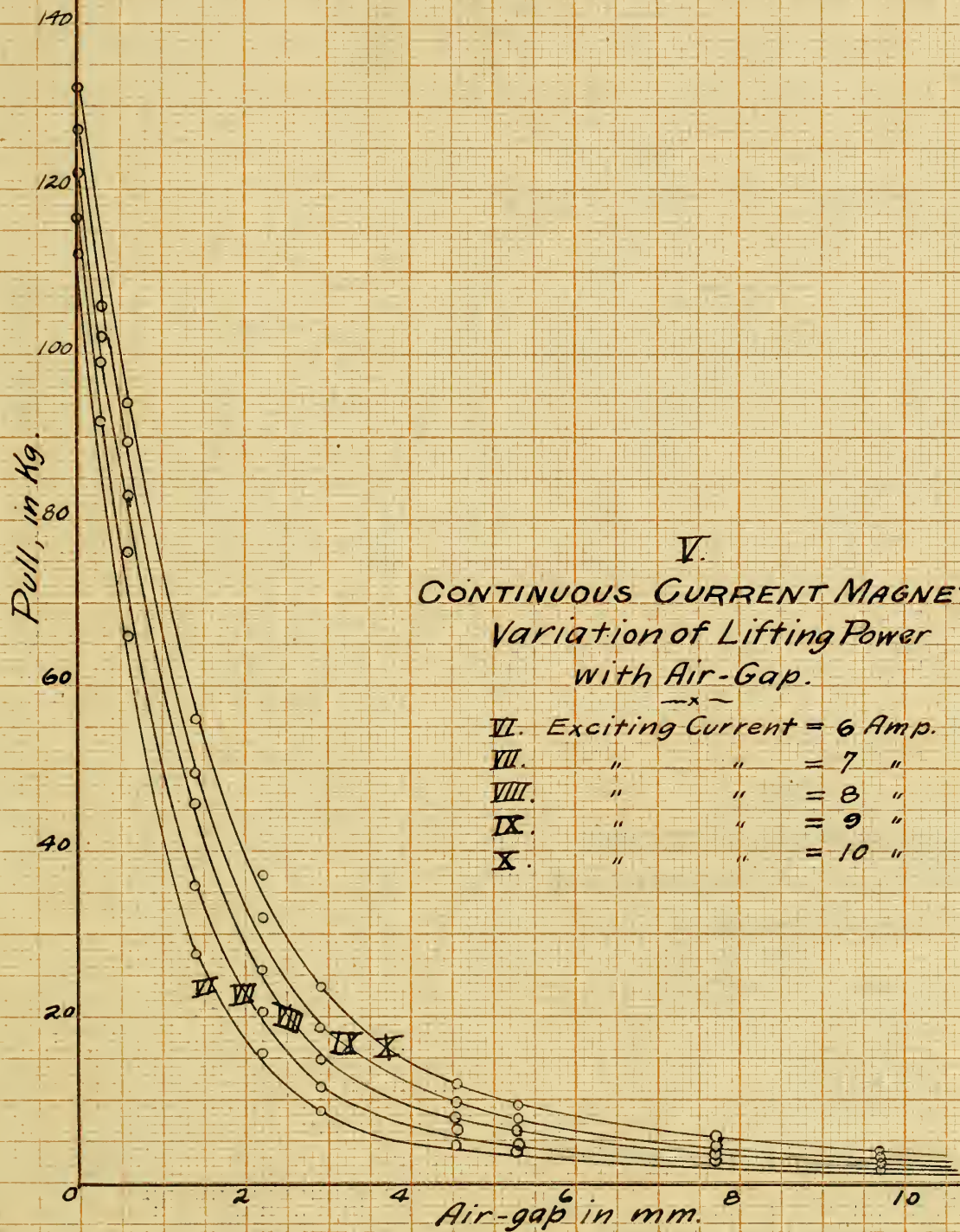
~x~

10. Air-gap = 0.692 cm.
11. " " = 0.968 "
12. " " = 1.206 "
13. " " = 1.680 "

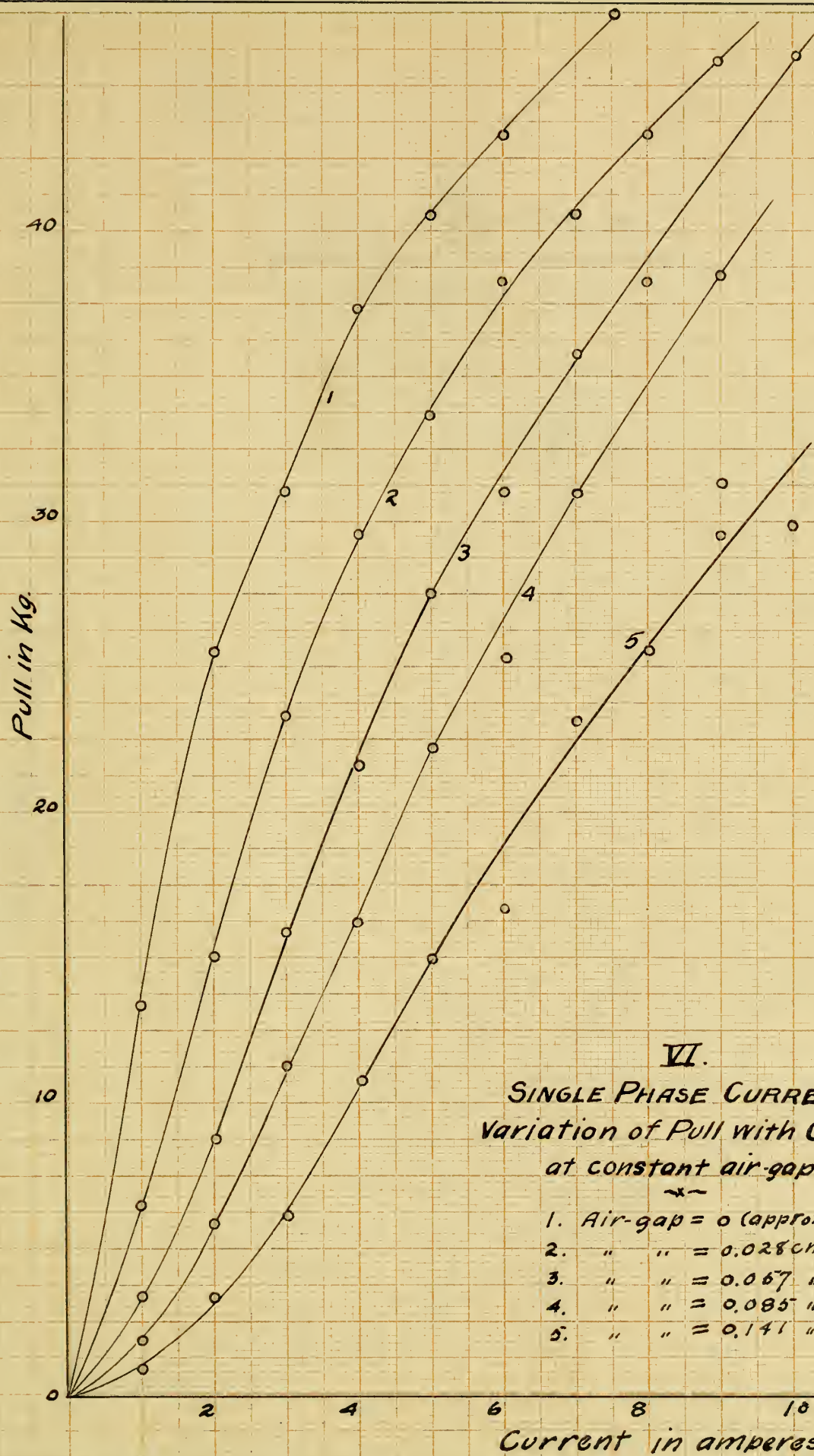












VI.
SINGLE PHASE CURRENT.
Variation of Pull with Current.
at constant air-gap.

- ~ ~ ~
1. Air-gap = 0 (approx).
 2. " " = 0.028 cm.
 3. " " = 0.067 "
 4. " " = 0.085 "
 5. " " = 0.141 "

VII.
SINGLE PHASE CURRENT.
 Variation of Pull with current,
 at constant air-gap.

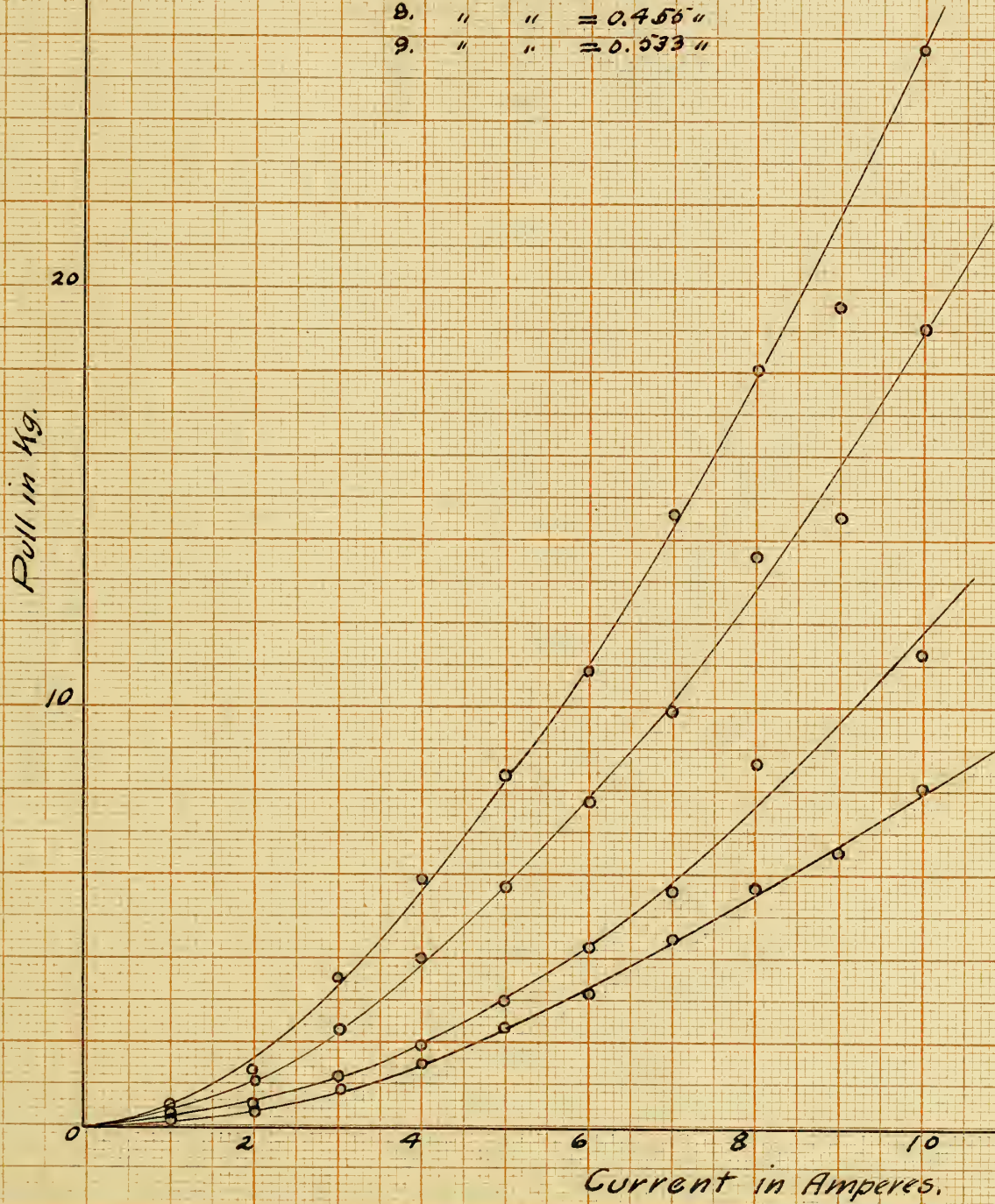
~*~

6. Air-gap = 0.219cm.

7. " " = 0.294 "

8. " " = 0.456 "

9. " " = 0.533 "



VIII.

SINGLE PHASE CURRENT
Variation of Pull with Current,
at constant air-gap.

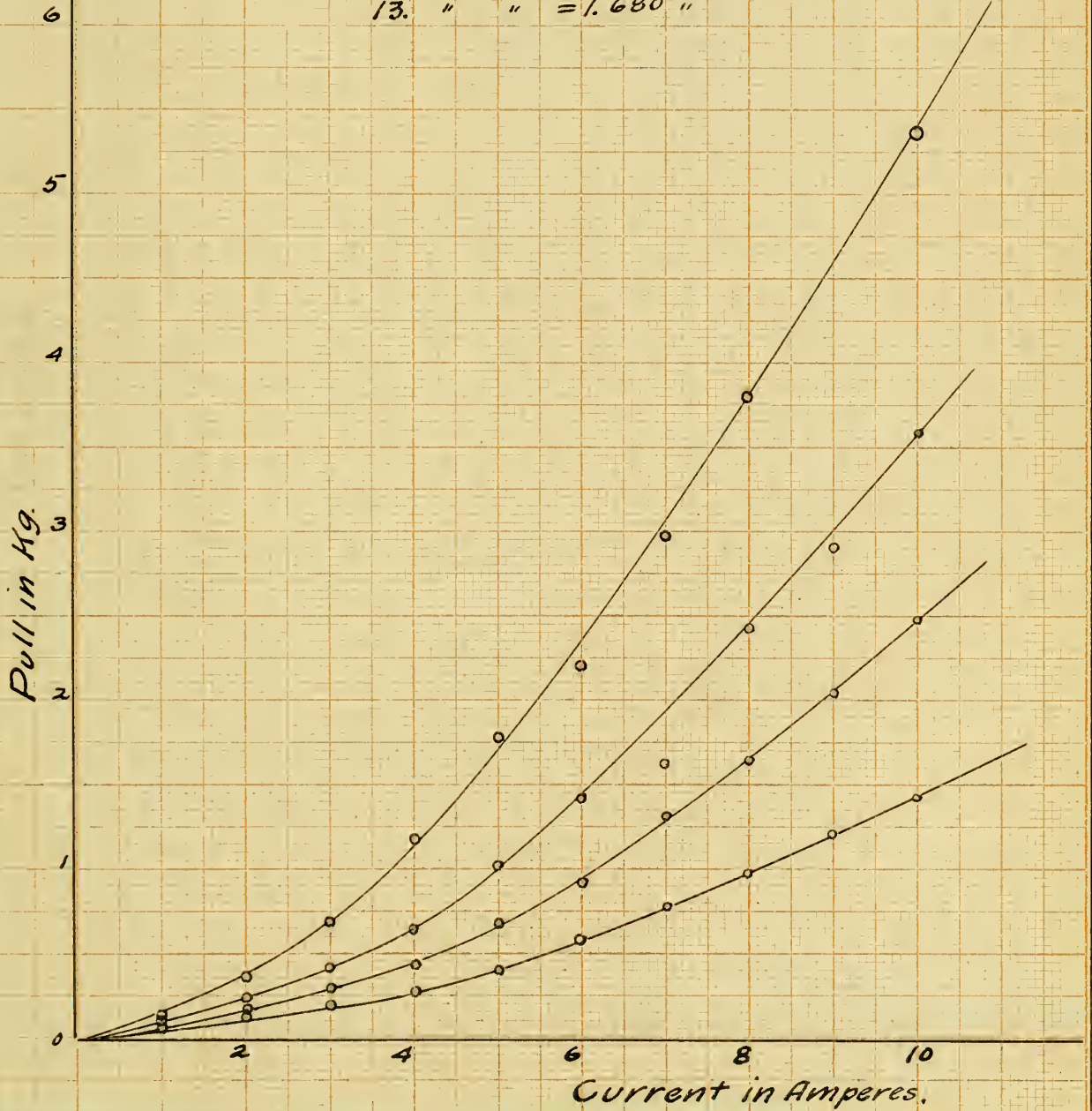
- x -

10. Air-gap = 0.692 cm.

11. " " = 0.968 "

12. " " = 1.206 "

13. " " = 1.680 "



IX.
SINGLE PHASE CURRENT.
Variation of Pull with Air-gap.

— x —

1. Current = 1 Amp.
2. " = 2 "
3. " = 3 "
4. " = 4 "
5. " = 5 "

Pull in Kg.

30

20

10

0

2

4

6

8

10

12

Air-gap in mm.

X
SINGLE PHASE CURRENT.
Variation of Pull with air-gap.

- x -

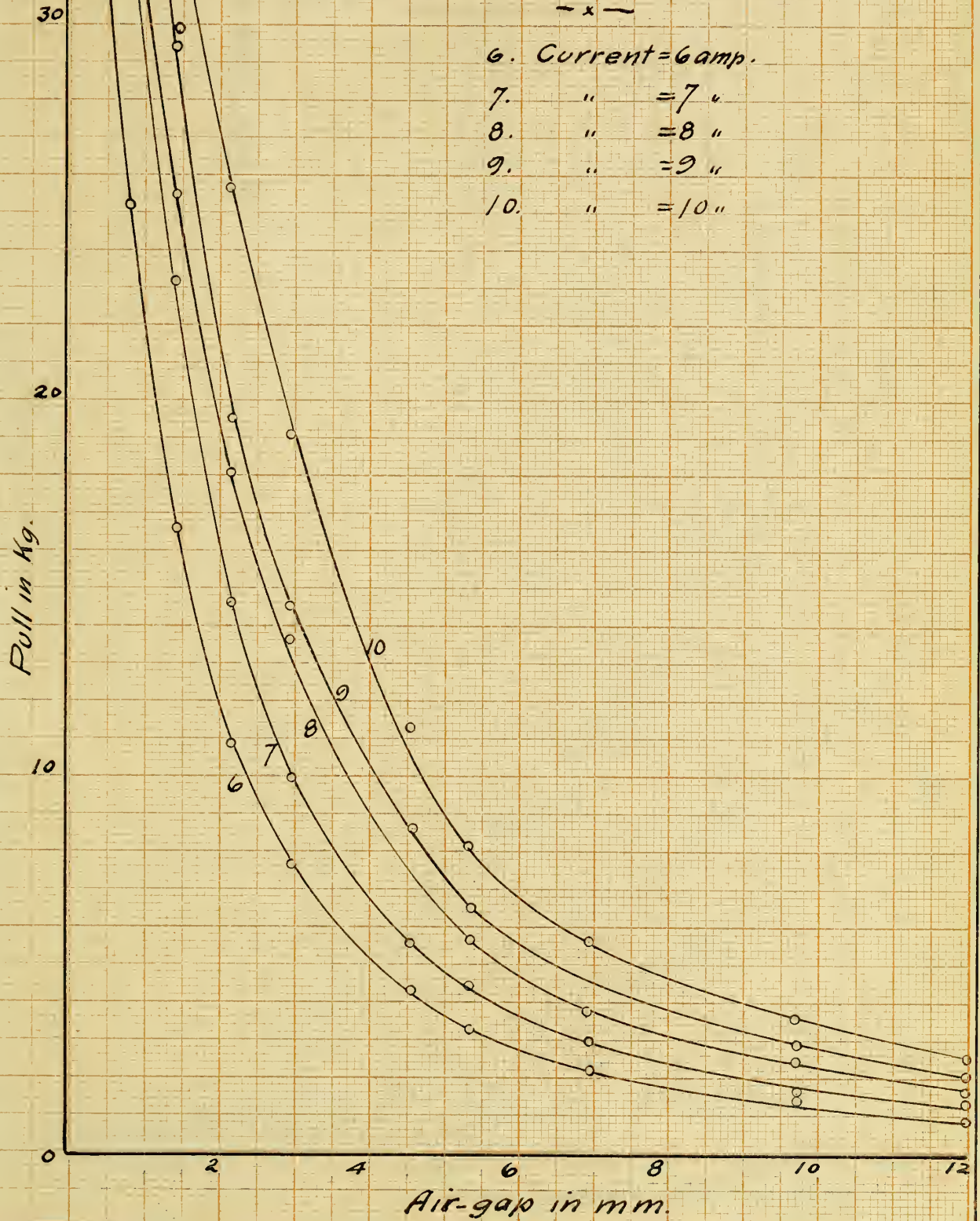
6. Current = 6 amp.

7. " = 7 "

8. " = 8 "

9. " = 9 "

10. " = 10 "



XI.

THREE PHASE CURRENT MAGNET. Variation of Lifting Power with Impressed E.M.F. per Phase

I. Air-gap ≈ 0 (Nearly).

II. " " = .0566 cm.

III. " " = .2179 "

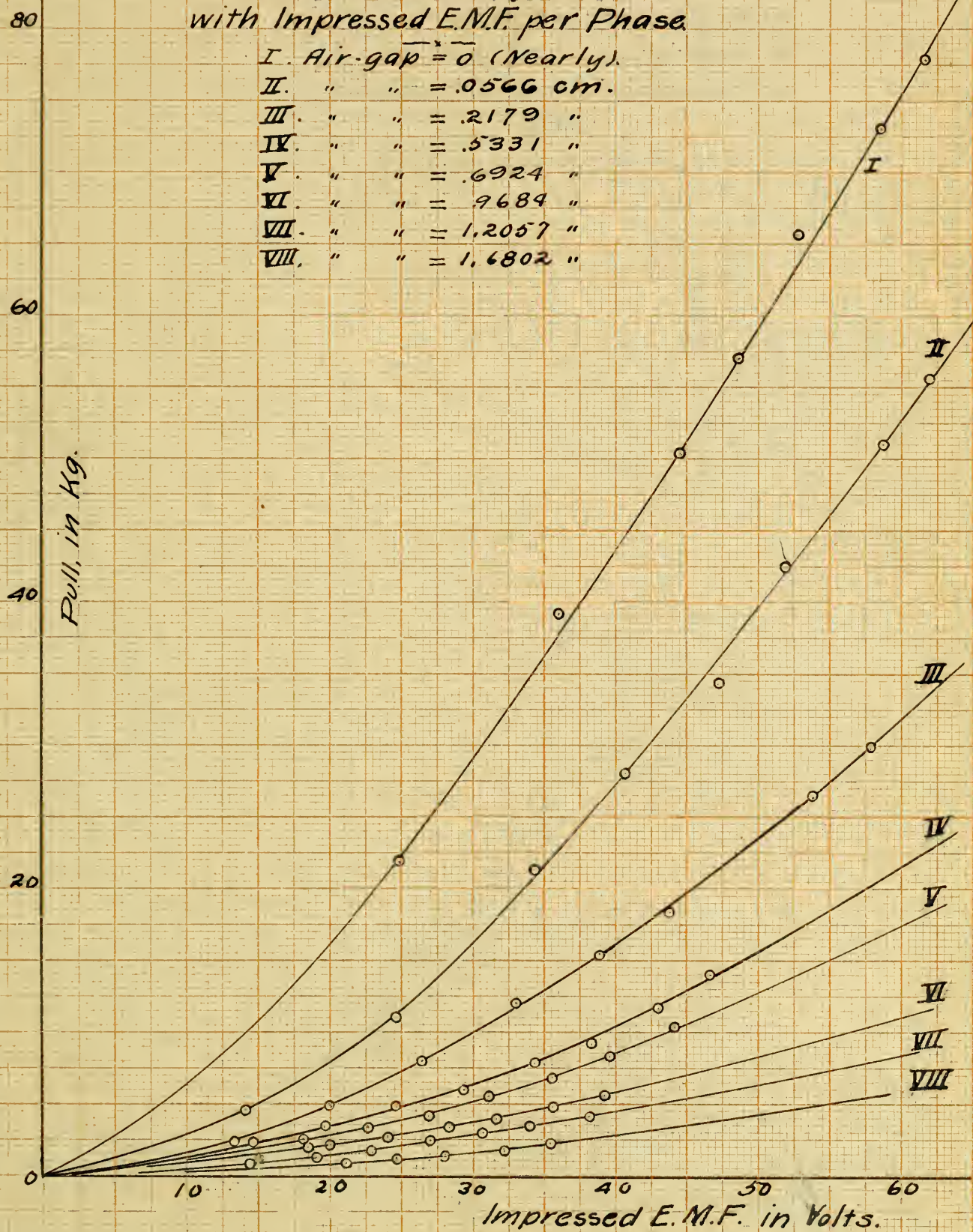
IV. " " = .5331 "

V. " " = .6924 "

VI. " " = .9684 "

VII. " " = 1.2057 "

VIII. " " = 1.6802 "



XII.

THREE PHASE CURRENT MAGNET.
Variation of Pull with Air-gap, at
constant impressed electromotive-
force.

I. Impressed E.M.F. = 10 Volts.

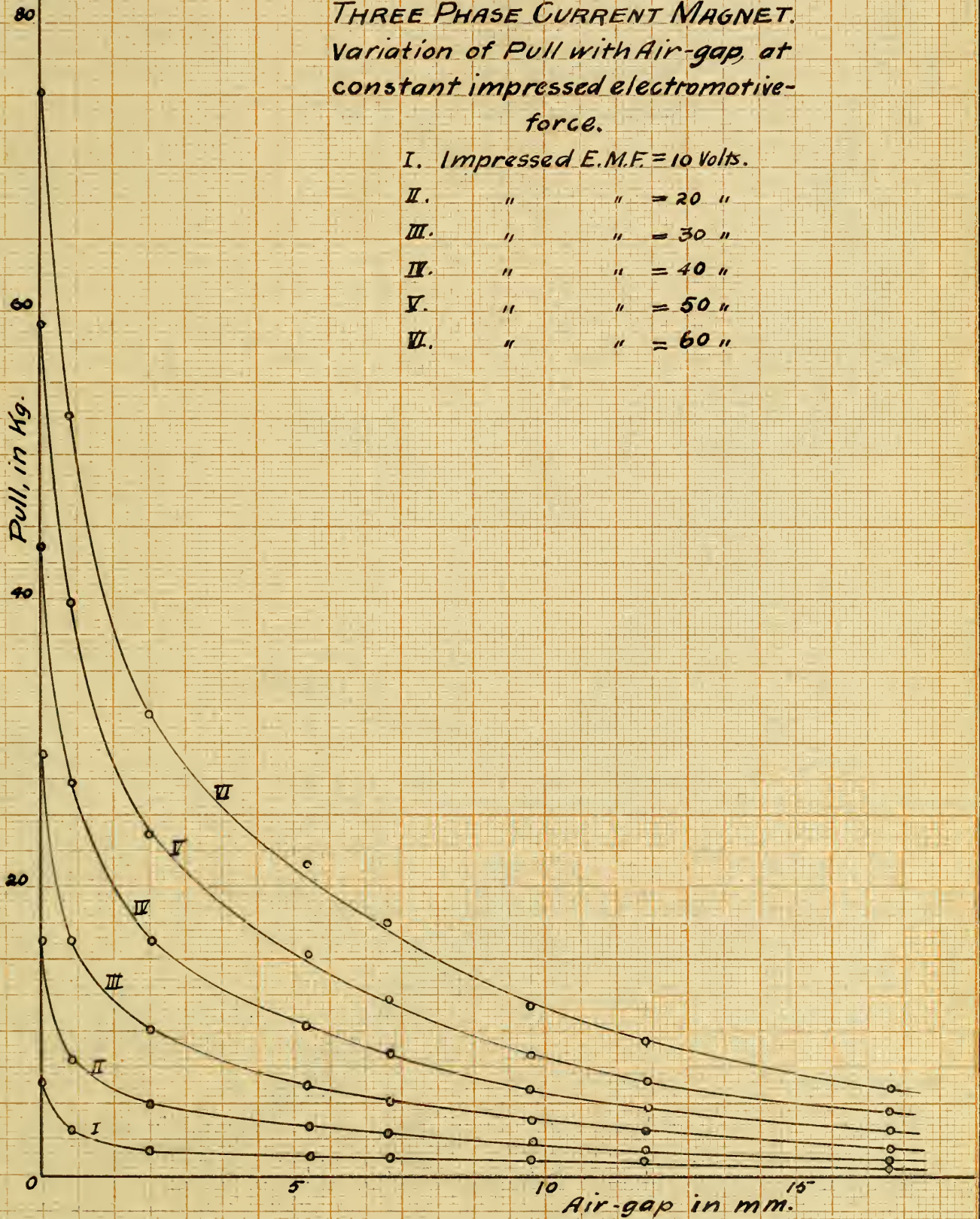
II. " " = 20 "

III. " " = 30 "

IV. " " = 40 "

V. " " = 50 "

VI. " " = 60 "

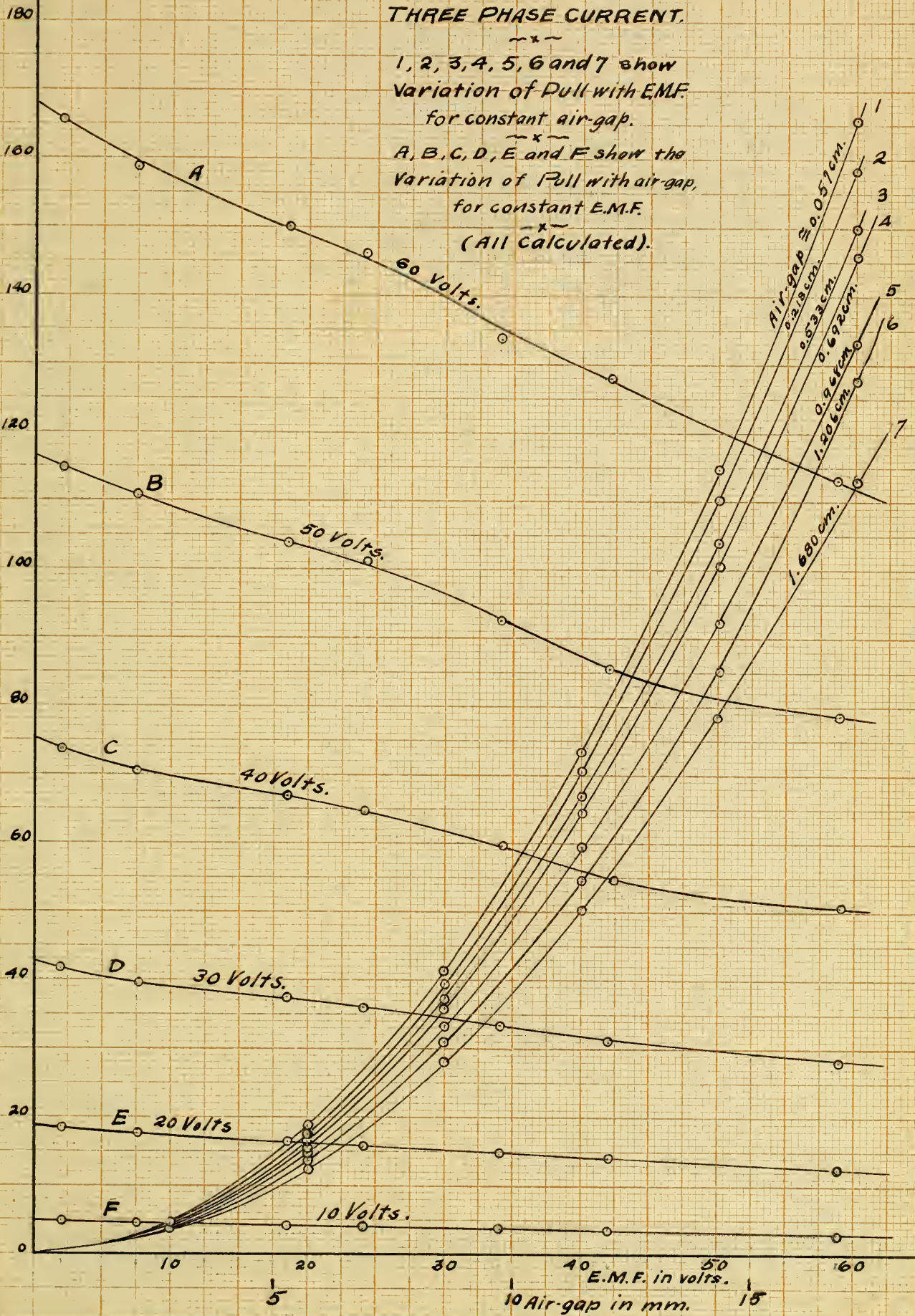


XIII.

THREE PHASE CURRENT.

1, 2, 3, 4, 5, 6 and 7 show
Variation of Pull with E.M.F.
for constant air-gap.

A, B, C, D, E and F show the
Variation of Pull with air-gap,
for constant E.M.F.
(All calculated).



Pull in Kg.

50

40

30

20

10

1

2

3

4

5

Air-gap in mm.

XIV.

SINGLE PHASE

Variation of Pull with Air-gap.
Determination of minimum
value of air-gap.

Pull in Kg.

50

40

30

20

10

1

2

3

4

5

Air-gap in mm.

Pull in Kg.

50

40

30

20

10

1

2

3

4

5

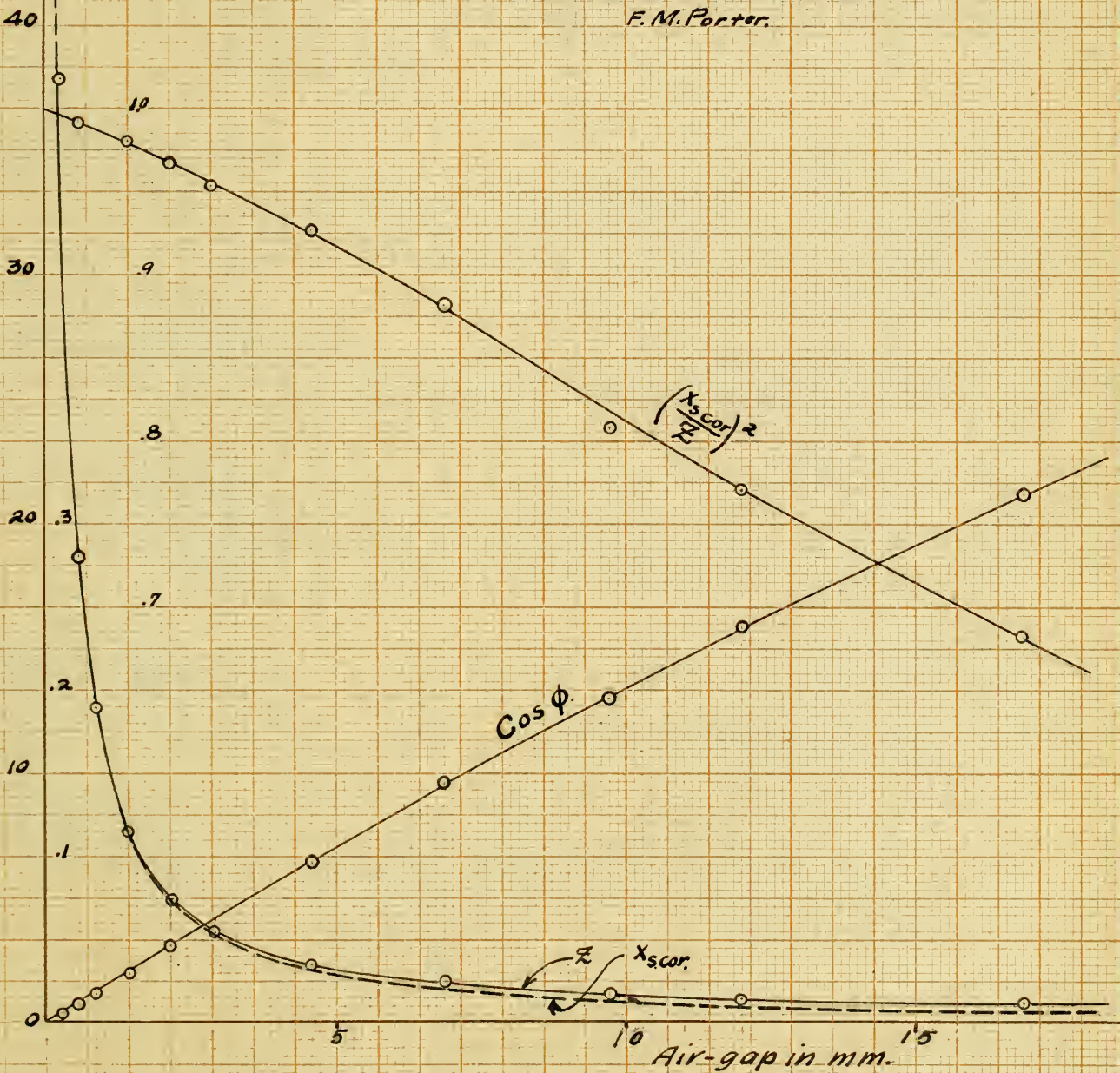
Air-gap in mm.

Z in Ohms.

XV.

THREE PHASE CURRENT.
Variation of Impedance,
air-gap reactance, cosine ϕ ,
with variation of airgap.

F. M. Porter.



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